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DETERMINATION OF OPTIMUM TROPIC STORAGE AND EXPOSURE SITES. PHASE II. PATTERNS AND PREDICTIONS OF TROPIC MATERIALS DETERIORATION

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The US Army Tropic Test Center in the Panama Canal Zone conducted a methodology investigation to determine time-decay curves describing the tropic material deterioration process and to develop a model for predicting deterioration from meteorological variables. The active portion of the project lasted from 1970–1973; and was performed in 16 sites that included coastal, forest, inland open, and shed exposure modes. Materials included steel, cotton, latex, butyl, polyvinyl chloride, and nylon. Samples were removed periodically and subjected to tensile

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Rainfall	Tropic coastal exposure sites	

Item 20. (cont)

tests. Meteorological measurements were also collected during exposure. Time decay curves with reasonably good fits were found in some cases but no generalized mathematical function was found applicable to all materials and all sites. In general, the linear model was superior, followed by double exponential and exponential.

Multiple regression correlations relating meteorological data to deterioration rates ranged from nonsignificant to only moderate in magnitude, and are considered poor predictors from both statistical and practical standpoints.

Recommendations included the adoption of experimental rather than correlational models in future studies; type of equations to use for specific material-mode combinations, and better definitions and measures of the tropic microenvironment.

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PREFACE

The present study lasted nearly three years including the planning, fieldwork and data analysis portions. During this time many persons who do not appear as authors made significant contributions. The originator of the project was Benjamin S. Goodwin, Chief Engineer, US Army Test and Evaluation Command. Other contributors include George W. Gauger, George F. Downs III, J. M. Calderon, CPT J. L. DiBenedetto, 1LT W. F. Lawson III, SP5 K. Griffis, and SP5 W. Hopfer of the US Army Tropic Test Center staff.

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Background

Concurrently with Phase I of the methodology investigation, *Determination of Optimum Tropic Storage and Exposure Sites* (references 1 and 2),* a Phase II was conducted to attempt mathematical modeling of the tropic material degradation process based on results of field exposures.

Sixteen field exposure sites and one laboratory control site were selected representing a reasonable cross section of tropical vegetation and terrain subenvironments available for testing in the Canal Zone. Six basic materials–steel, nylon, polyvinyl chloride, natural rubber (latex), butyl rubber, and cotton were exposed on racks located at each site. The study systematically varied time of exposure by emplacing material specimens during four climatic phases: early dry season, late dry season, mid wet season and late wet season. Exposure modes included open sites, sheds, forest sites, coastal sites, and a mangrove site. Specimens were removed at systematic intervals and subjected to laboratory analyses that included tensile strength, tensile elongation, visible/ultraviolet light reflectance, microbiological inspection, and visual ratings. Climatic data and salt fall were gathered during the course of the study. Detailed analyses comparing site severity and seasonal effects are reported separately in *Determination of Optimum Tropic Storage and Exposure Sites,* Report II.

Objectives

The objectives of the investigation were as follows: (a) to find a generalized decay formula describing the degradation properties of materials as a function of tropic exposure time, and (b) to develop a mathematical prediction model relating meteorological variables to deterioration measurements.

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* **Downs and Lawson.** ***Determination of Optimum Tropic Storage and Exposure Sites, Report I: Survey of Programs in Tropic Materials Research,*** **TECOM Project No. 9 CO 009 000 006, April 1973.**

Sprouse, Neptune, and Bryan. ***Determination of Optimum Tropic Storage and Exposure Sites, Report II: Empirical Data,*** **TECOM Project NO. 9 CO 009 000 006, March 1974.**

SECTION 2. DETAILS OF INVESTIGATION

The Search for an Appropriate Decay Formula

The study was started under the assumptions that (a) a property of materials exists that can be used as a measure of the degree of degradation. The property is denoted in this report by the letter y; (b) there is one general formula that describes the degradation process of all materials as a function of time t; and (c) constants in the formula are functions of known environmental factors and of known physical properties of the materials.

Although no such general formula was found, those attempted will be discussed in the following paragraphs. These discussions may aid future researchers.

The search for one overall formula was begun under the assumption that deterioration begins slowly, then speeds up for some period of time, and then decreases asymptotically. A curve that has these properties is:

$$y = y_0/2 + a \text{ arc sine } (bt - \frac{\pi}{2}) \qquad (1)$$

Such a formula is extremely difficult to handle when there are more pairs (y, t) than unknowns.

A curve that almost has the postulated properties is:

$$t = a + by + cy^2 + dy^3 \qquad (2)$$

(Note: The constants in all formulas are designated by a, b, c, etc.; they are not the same values from formula to formula). If the curve is forced to go through the point ($t = 0$, $y = y_0$) then equation (2) reduces to:

$$t = b(y - y_0) + c(y^2 - y_0^2) + d(y^3 - y_0^3) \qquad (2a)$$

This is a true prediction formula which yields the time of exposure (t) after which the material's property (y) has decreased from y_0 to y. The factors b, c, and d can easily be obtained through the least square procedures.

One big disadvantage immediately became evident in formula 2a and another disadvantage became evident later. As with all power polynomials, the factors (b, c, and d) have only formal mathematical significance; small changes in the data will produce a small change in the appearance of the curve but may be accompanied by large changes in the coefficients. On the other hand, small changes in the coefficients may produce essential changes of the curve. The consequence is that the coefficients cannot be related to any physical variables that influence the measured ys.

In addition to the formal objections against formulas (2) and (2a). the basic assumption of a monotonic decrease of physical properties with time is not always realized, and such particularities cannot be reflected by functions of the types (2) and (2a).

The formula shown below:

$$t = a(y - y_o) + b(y^3 - y_o^3) + c(y^5 - y_o^5) \tag{3}$$

is an improvement over formula (2a) because the residual errors (the sum of the least squares) is smaller than in (2a). However, the basic objections against (2a) also apply to formula (3).

Trigonometric polynomials avoid some of the pitfalls of the power polynomials because their coefficients have a geometric meaning; their goodness of fit can be improved by adding new constants without changing the values of those constants previously obtained. Trigonometric polynomials are also able to reflect any anomaly such as a period of improvement within the general pattern of deterioration. The general formula of this type is:

$$y = a_o + \Sigma p_i \text{ sine it} + \Sigma q_i \cos it \tag{4}$$

Formula (4), though an improvement over (2) and (3), has the following three disadvantages: (a) the downward trend dictated by the measurements will change into an upward trend, either in extrapolation beyond empirical data or perhaps even earlier; (b) the formula is too flexible because it overreacts to irregularities instead of smoothing them out; (c) the prediction looks for t, not for y, and a trigonometric polynomial cannot easily be reversed.

Objection (b) of the preceding paragraph can be removed by the following more flexible approach.

$$y = a_o + p \text{ sine } (t + bt^2) + q \cos (t + bt^2) \tag{5}$$

This formula cannot be subjected to a least squares procedure,* rather b must be found through trial and error. This can be done quickly by a computer and is not a serious argument against the use of (5). However, objections (a) and (c) to formula (4) also apply to formula (5). Furthermore, objection (b) is removed at the expense of a substantially worse fit. The following formula:

$$y = a/[1 + b(t - t_m)^2] \tag{6}$$

has fewer disadvantages than any of those discussed so far. The time t_m is the time when the deterioration curve is at its maximum, b reflects the steepness of the curve, and a reflects the value of the extreme. If the curve is forced to pass through the point $t = 0$, $y = y_o$, then $a = y_o(1 + bt_m)^2$, and:

$$y = y_o \frac{1 + bt_m^2}{1 + b(t - t_m)^2} \tag{6a}$$

* A harmonic polynomial, equation (4), automatically fulfills the least squares condition whichever is larger.

This formula also has some serious disadvantages despite definite improvements over formulas (1) through (5). It cannot readily be subjected to a least squares procedure, it gives two solutions for t_m, and it is not obvious that y is at a maximum at t_m (t_m can also denote a minimum). In addition, the second power together with the factor b does not provide enough flexibility to achieve a good fit in many of the actually measured data series. A marked improvement could be achieved if a formula of the type

$$y = y_o \frac{1 + bt_m{}^c}{1 + b(t - t_m)^c} + d \tag{6b}$$

were manageable. Unfortunately, this is not the case and the approach was dropped.

Further comparison of analytical curves with actual data showed that there is no single manageable function that can be used for all types of deterioration. It was then decided to use three different functions and select the one with the best fit on an individual basis.

The three curves were defined by the following formulas:*

$$\hat{y}(1) = gt + h \tag{7}$$
$$\hat{y}(2) = y_o e^{at + bt^2} \tag{8}$$
$$\hat{y}(3) = y_o e^{ct^u} \tag{9}$$

Formula (7) represents a straight line and is the simplest formula possible. Formulas (8) and (9) represent curves which have much similarity with some of the actual decay curves and yet are mathematically simple to manage. The coefficients were computed through least squares procedures,† then the error term $\Sigma(y - \hat{y})^2$ was calculated for each of the three approximations.

Meteorological Analysis

In an attempt to relate material degradation to weathering, correlation coefficents were computed between certain physical properties and available weather parameters. These comparisons were made after an 84-day exposure for each material. This time period for which the comparisons had to be made posed some analysis problems. It was desirable to have periods in which weather patterns did not change substantially. Unfortunately, short term unseasonal changes in weather patterns did occur during some phases. These fluctuations caused lack of comparability in some results and implied the need for long exposure periods so that short lived weather patterns were overshadowed by seasonal patterns. Another factor, calling for long exposure was the low decay rate of some materials. The decay rate differences were so great that neither low decay rates nor high decay rates were properly reflected in the computation. It was decided to exclude the highest decay-rate materials—latex—and the lowest—butyl.

* Hereafter FORTRAN notation is used to present long expressions in the exponent more clearly; $\hat{y}(1)$ = g*t + h, $\hat{y}(2)$ = y_o*Exp(a*t + b*t**2), and $\hat{y}(3)$ = y_o*Exp(c*t**u).

† This was always possible for (7) and (8); (9) could not be solved when any observed y was greater than y_o.

The following materials and weather parameters were established for as many exposure sites as possible for use in a linear regression analysis: (a) tensile strength (also weight loss for steel); (b) average daily maximum temperatures, T_x; (c) average daily values of absolute humidity, H; (d) rainfall total accumulated during the 84 days of exposure, R; and (e) the daily average of salt accumulation on salt candles, S. Correlation coefficients were computed across sites.

Details of measurements follow:

Temperature: It was not possible to include solar radiation. Indirectly, radiation is indicated in the maximum temperature measurements. Although the correlation between radiation and maximum temperature is very high at any particular site, the regression equation changes from site to site mainly as a result of varying wind conditions. As an example, the regression equations between daily total visible radiation, E, and maximum temperature, T_x, may be compared for two sites, Gun Hill and Chiva Chiva, which were only 1.3 miles apart. The equations were:

Gun Hill: $$T_x = 0.0210\ E + 78.7 \qquad (10)$$

Chiva Chiva: $$T_x = 0.0200\ E + 81.5 \qquad (11)$$

Within the small range of temperatures, the difference in the absolute terms has a great influence, e.g.,

200 langley/days cause the temperature to rise to 82.9°F at Gun Hill
to 85.5°F at Chiva Chiva
600 langley/days cause the temperature to rise to 91.3°F at Gun Hill
to 93.5°F at Chiva Chiva

Since 200 and 600 langley/days are good approximations of the absolute extremes of visible radiation in the Canal Zone, the temperature differences of 2.6°F, (85.5°- 82.9°) and 2.2°F, (93.5°- 91.3°) between the sites are close to 30 percent of the entire range of maximum temperatures. This means that maximum temperatures at other sites were indicative only of the radiation levels existing at those sites. In addition, radiation under a forest canopy may change substantially at very short distances, e.g., from one exposed material sample to its neighbor, whereas the ambient temperature does not reflect such differences.

Humidity. The relative humidity is mainly a function of temperature and must be associated with temperature to reveal actual moisture content of the air. The absolute humidity represents the amount of water vapor in the air and since it changes very little in the course of the day (except when the entire air mass is exchanged through a weather event, which occurs rarely in the tropics) this parameter was chosen for the regression analysis. It was computed from the highest temperature and the lowest relative humidity.

The absolute humidity was expressed as vapor pressure. The choice of this parameter from several others was arbitrary and has no consequence other than affecting the magnitude of the computed constants.

Rainfall. It would have been preferable to add another variable to the amount of accumulated rainfall, namely the number of occurrences of rain and dew. It is possible that the presence of small amounts of liquid water on the samples has as much or even more effect than total rainfall. At the time of the project, instrumentation was not available to monitor the wetness of the samples. Total rainfall data were available.

The actual seasons deviated from the normal; the intended dry season phase of the project began with frequent rains. As a consequence, the smallest rainfall total during the first 84 days of exposure was 5.9 inches. The sheds are substitutes for no-rain conditions with the constraints, however, that the sheds also block out all direct and most of the diffuse radiation. Direct radiation is very high in rainless periods. Together with the radiation blocking effect, the sheds also prevent dew formation. The correlation coefficients presented indicate that the introduction of zero rainfall for shed sites was of no important statistical consequence except for steel and to a slight degree for cotton.

Salt. Airborne ocean salt was measured by the salt candle method (reference 3).* The salt deposited on the candles at each exposure site was collected monthly, and analyzed for total chloride content. It was then used to estimate mean daily deposits and used in the regression analysis.

There were 50 (58 for steel) cases for which data were available to perform a regression analysis. The cases were distributed as shown below, with dashes (–) representing missing data.

		Exposure Phase				
	Site	I	II	III	IV	V†
Coastal:	Flamenco Island	–	X	X	X	X
	Galeta Beach	–	X	X	–	X
Open Inland:	Gun Hill	X	X	X	X	–
	Chiva Chiva	X	X	X	X	X
	Gamboa	X	X	X	X	–
	Fort Gulick	X	X	X	X	–
	Coco Solo	X	X	X	X	X
	Fort Sherman	X	X	X	X	–
Shed:	Chiva Chiva	X	X	X	X	–
	Fort Gulick	X	X	X	X	–
	Coco Solo	–	X	X	–	X
Forest:	Fort Clayton	X	X	X	–	–
	Coco Solo	–	X	X	–	X
	Fort Sherman	X	X	X	X	X
Mangrove:	Coco Solo	–	X	X	–	X

* Foran, Gibbons, and Wellington. *The Measurement of Atmospheric Sulfur Dioxide and Chlorides*, Journal of Chemistry in Canada, May 1965.

† Steel, only.

The Summary of Results, below, shows that the missing data did not significantly influence the computations.

Summary of Results

• Generalized Materials Decay Formula

Curves and Time Series. Although several physical properties of the materials were measured, only the curve fitting of the tensile strength data was analyzed because tensile strength is the only numerically measurable property for all materials.

The slope of the "deterioration curves," i.e., the change of tensile strength as a function of exposure time, depends on several factors. Disregarding measurement and random errors, these factors are: material characteristics, microenvironmental characteristics of the exposure site, seasonal effects, and weather effects.

Appendix C lists the smoothed values of tensile strength. For better comparability, all values are expressed in percent of the "standard value," which is the tensile strength of the material on the day it was put on exposure. Changes in tensile strength for each material (except butyl) with exposure time are given for (a) each site and each phase, (b) each site, all phases combined, (c) each phase, similar sites combined, (d) all phases combined for similar sites. In the following discussion the grouping of similar sites will be referred to as "exposure mode" (shed, forest, coastal, open). (In addition to the smoothed values, appendix C also lists the standard error of estimate σ_{yx}.)*

Table 1 lists the frequency of the curves that resulted in the smallest σ_{yx}. There were many cases in which the error terms for the curves were almost equal. The following conventions were followed. Call σ_{yx_1} the standard error of one of the curves, σ_{yx_2} the error of another curve. When $\sigma_{yx_1} - \sigma_{yx_2}$ was smaller than $1/40(\sigma_{yx_1} + \sigma_{yx_2})$, i.e., the difference was less than 5 percent of the average of both errors, a tie was determined. The tied cases were evenly distributed among the types of curves in table 1. Table 1 shows the frequency of occurrence of best fit curves. Appendix C lists real data of tensile strength changes with time.

Table 1 shows that some materials have deterioration curves that, with few exceptions, follow the same pattern. In general, linear was the best fit. The mean curves for each material and for each exposure mode, together with the data points on which the curves are based, are presented in figures C-1 through C-5. These curves represent the same data which are marked as summarizations in appendix C.

Steel. Figure C-1, a through d, shows deterioration curves that are best approximated by either straight lines or by parts of exponential curves where they are almost straight. Steel reacts strongly to moist salt (coastal). The high humidity of the forest, frequently coupled with permanent wetness of the samples, is not as deteriorative as the radiation and wet-dry cycles at the open sites.

* $\sigma_{yx} = [\Sigma(y - \hat{y})^2/(n-2)]^{1/2}$ where $\hat{y}$ is the estimate, y, the measured value, or $\sigma_{yx} = \sigma_y\sqrt{1 - R_{xy}^2}$.

Table 1. Percentage Occurrence of Best Fitting Curves

Sites	Linear $\hat{y} = g*t + h$	Exponential $\hat{y} = y_o*Exp(a*t + b*t**2)$	Double Exponential $\hat{y} = y_o*Exp(c*t**u)$
Steel			
Coastal	65	35	0
Open inland	67	31	2
Shed	73	23	4
Forest	58	25	17
Cotton			
Coastal	19	31	50
Open inland	73	27	0
Shed	58	25	17
Forest	25	75	0
Nylon			
Coastal	0	17	83
Open inland	0	0	100
Shed	61	22	17
Forest	55	37	8
PVC			
Coastal	50	31	19
Open inland	76	24	0
Shed	71	25	4
Forest	38	56	6
Latex			
Coastal	0	0	100
Open inland	5	0	95
Shed	42	8	50
Forest	56	0	44

Cotton. Figure C-2, a through d, shows deterioration of cotton best described by a straight line. For predicting cotton deterioration, the straight line provides a safety margin over the exponential formula since, from the fourth month on, the former predicts more rapid deterioration than the exponential.

Nylon. Figure C-3, a through d, presents deterioration patterns that are quite different from those of steel (figure C-1) and cotton (figure C-2). In particular, the decrease of tensile strength at sunny sites (open and coastal) is quite rapid at the beginning of the exposure time, then levels off. Deterioration in the sheds, though less than at open sites, is more rapid than in forests.

Polyvinyl chloride. Figure C-4, a through d, shows forest effect even stronger. There is a slight but inconclusive indication that the tensile strength may suddenly break down after the length of exposure time used in this project. Obviously, no extrapolation is possible until longer exposure periods are used.

Latex. For latex, (figure C-5, a through d) a decrease of tensile strengths best described by the double exponential function, occurred at all open and at half of the covered sites (table 1). This decrease depends on the amount of sunlight available. Open sites showed more rapid deterioration than covered sites.

Errors of Prediction. Appendix C lists the standard errors of estimate in addition to the smoothed values of tensile strength. Table 3 shows that these errors decrease with increasing number of data series. The first row of table 2 shows the average error for an individual series of data, i.e., series for one site and for one exposure phase. The remaining rows show the average errors from condensed data. These condensations were done in three ways: (a) the available phases averaged, but the sites separated; (b) all sites of an exposure mode averaged, but the phases separated; and (c) all exposure modes averaged over all phases.

Table 2. Average Standard Errors of Estimate (Percent of Standard Value)

	Steel	Cotton	Nylon	PVC	Latex
Individual time series	5.42	6.34	6.95	5.92	5.06
For each site, all phases combined	2.52	4.24	4.25	3.23	4.59
For each phase, all sites of a mode combined	3.47	4.59	4.75	4.22	3.97
All phases, all sites of a mode combined	1.28	3.02	3.20	2.90	2.70

With the exception of latex the combination of phases decreased the error more than the combination of sites. There are two reasons for that. First, the rainy season in the Canal Zone is much longer than the dry season, consequently most of the exposure was done under comparable weather conditions. Second, the timing of the exposure periods (phases) did not completely coincide with actual weather events. This finding only reinforces a fact that has been known for some time by tropic testers: Tensile measurements of items exposed in the natural environment are highly variable and many replications are necessary to stabilize environmental effects.

Review of appendix C shows that the selection of forest sites in particular has a great influence in the deterioration effect. Table 3 gives a numerical summary.

Table 3. Average Standard Errors of Estimate (Percent of Standard Value)

	Coastal	Open Inland	Shed	Forest
Individual time series	5.59	4.90	5.82	6.84
For each material, all phases combined	3.56	3.02	3.25	4.40
For each phase, all materials combined	3.75	3.23	4.06	5.65
All phases, all materials combined	2.72	1.88	2.18	3.18

The table demonstrates that the prediction is most accurate for open inland sites. This coincides with the findings that deterioration is generally greatest at open sites. Table 4 supports the latter statement through comparison between open and covered sites. The influence of sunlight on deterioration is clearly represented.

Table 4. Tensile Strength at End of Exposure (Percent of Standard Value)

All phases and all sites within an exposure mode combined.

	Coastal	Open Inland	Sheds	Forest
Steel	37	67	89	70
Cotton	38	59	84	41
Nylon	23	26	37	80
PVC	65	59	93	97
Latex	5	5	26	54
Average	34	41	66	68

Up to this point only errors were discussed that apply to data series as entities. It is also appropriate to discuss the change of error with prediction time.

In predicting a single dependent variable (tensile strength) from multiple predictors over a span of time, the absolute accuracy of the predictions is dependent on two quantities, the multiple regression coefficient R and the standard deviation of the dependent variable σ_y. Even when R is high, a large σ_y limits the predictive accuracy of forecasts, viz $\sigma_{yx} = \sigma_y\sqrt{1 - R^2}$. The pattern obvious in the present study is for tensile strength means to decrease with exposure time, and for σ_y to increase until the point of near total deterioration is reached, at which time both the mean and σ_y approach zero. A weakness of tensile strength as a predictant is the fact that variability does increase with exposure. This can be observed in table 5 where means and σ_y's of short and long exposures are compared in the controlled and natural environments. Coefficients of variation, which express the variance of σ_y relative to its own mean as a percentage, are also presented.

Fifteen of 20 possible comparisons show higher variability after longer exposures. The apparent reversals were latex and nylon at open and coastal sites and the control environment for cotton. The first two exceptions result from extremely rapid deterioration in the first weeks of exposure. At some point after the major portion of deterioration has occurred the trend of increasing variability reverses. However, the trend of widening dispersion is evident in early samples. Consequently, these so called reversals are not contrary to the general hypothesis of limited accuracy in forecasts of tensile measurements.

The crux of this general trend is that prediction of deterioration becomes less accurate at the time when accuracy is most needed--at the longer exposure times for relatively benign sites and when deterioration is rapid at more severe sites. This finding emphasizes the need for a valid alternative to tensile tests as a measure of deterioration.

Table 5. Comparison of Variability in Tensile Measurements for Four Materials in Five Exposure Modes*

Type Material	Exposure Mode	Exposure Time (days)	Mean (kg)	Standard Deviation	Coefficient of Variation (%)
Steel	Control	7	162.3	2.9	1.8
		70	164.5	3.7	2.2
	Coastal	7	148.2	11.8	8.0
		70	76.4	30.6	40.0
	Shelter	7	160.3	7.5	4.7
		70	144.1	10.8	7.5
	Forest	7	156.4	8.9	5.7
		70	122.0	23.3	19.1
	Open	7	152.8	6.9	4.4
		70	117.4	15.4	13.1
Latex	Control	7	10.12	0.7	6.6
		70	9.19	1.43	15.4
	Coastal	7	2.94	1.23	42.0
		70	0.68	0.06	9.1
	Shelter	7	7.54	2.57	34.2
		70	3.33	2.24	67.3
	Forest	7	8.63	1.71	19.8
		70	5.94	1.99	33.2
	Open	7	2.86	1.85	64.7
		70	0.72	0.09	12.8
Nylon	Control	28	15.5	1.35	8.7
		280	16.6	2.19	13.3
	Coastal	28	7.7	2.21	28.8
		280	3.7	1.03	27.7
	Shelter	28	14.1	1.94	13.8
		280	7.3	3.56	48.9
	Forest	28	14.9	1.15	7.7
		280	12.6	2.74	21.7
	Open	28	9.4	1.87	20.2
		280	4.7	0.63	13.3
Cotton	Control	14	130.3	7.11	5.5
		140	130.5	3.02	2.3
	Coastal	14	134.8	9.16	6.8
		140	64.8	15.27	23.6
	Shelter	14	134.1	11.26	10.6
		140	112.9	18.86	16.7
	Forest	14	142.4	10.54	7.4
		140	81.0	42.60	52.7
	Open	14	138.1	7.37	5.3
		140	94.2	13.87	14.7

* Butyl and PVC were not included in this analysis since decreases in tensile measurements were very gradual and standard deviations small.

Predictions. Table 6 presents estimates of the exposure times after which the tensile strength of the different materials has decreased to 90, 75, and 50 percent of its original value. The 90 percent indicates the time in which practically no measurable deterioration occurs, the 75 percent indicates material that is still useful, the 50 percent represents failed material by the definitions used in this report. Appendix C shows other percentage values than those produced in the following paragraphs.

The numbers in the table indicate the average time, in days, after which the tensile strength had decreased to the percentage indicated. Dashes (——) mean that either the measured values varied too much to provide even a tentative basis for a prediction, or that the computed value was too far beyond the time frame in which the measurements of this project were made to be realistic. Values in parentheses ( ) are considered reasonable extrapolations beyond the observation period.

Table 6. Average Time (Days) for Tensile Strength to Decrease to 90, 75, and 50 Percent of Original Strength

	Coastal	Open Inland	Sheds	Forests	Mangrove
(a)		90 Percent			
Steel	12	26	77	21	2.2
Cotton	30	85	107	44	121
Nylon	1	0.8	52	174	62
PVC	67	75	——	——	——
Latex	0.0003	0.0003	1.1	2.5	0.34
(b)		75 Percent			
Steel	30	59	——	63	6.3
Cotton	70	110	——	148	(180)
Nylon	9	9	127	——	146
PVC	213	202	——	——	——
Latex	0.010	0.013	6	18	2.1
(c)		50 Percent			
Steel	65	——	——	——	16
Cotton	138	——	——	——	——
Nylon	64	72	258	——	307
PVC	——	(417)	——	——	——
Latex	0.31	0.35	28	(106)	10

From these data it is hypothesized that PVC will deteriorate slowly at first, then at some point deterioration will increase catastrophically and tensile strength will rapidly approach zero. To test this hypothesis a longer exposure time would be necessary.

• Meteorological Variables as Predictors of Deterioration

The approximation, $\hat{y}$, of the physical property, y, was done by means of multiple regression: $y = aT_X + bH + cR + dS + e$. The constants a, b, c, d, and e, obtained through least square procedures, are listed in appendix C; the values of the variables are also listed in appendix C. The latter were previously discussed in more general terms. No data for latex were used because of its high decay rate mentioned above. For steel more data were available for analysis because a fifth exposure phase was added for this material.

It was stated previously that doubts may arise that sheds can be considered sites with zero rainfall, and used in the computation together with other types of sites. Their use or non-use produced discrepancies only for steel and cotton; the results of computations for both materials are presented in the following paragraphs.

Mangrove has dramatic and rapid effects on steel (reference 2).* For this reason regression curves for steel excluded the mangrove site.

There are two kinds of associations between the variables of the regression equations. The first is represented by the zero-order correlation coefficient in which two variables are related as if none of the other variables influence either of them. The second is the partial correlation coefficient that statistically controls the influence of the other variables. Table 7 lists all zero-order correlation coefficients. The original data, listed in appendix C, indicate which sites and exposure periods were used in the computations.

Among the meteorological predictor variables, only the correlation between absolute humidity–H, and rainfall total–R, is statistically significant (.45) at the 1 percent level. When the zero values of rainfall were removed by excluding the sheds from the analysis, r(H, R) dropped to .32 which remains significant at the 5 percent level.

Although the zero-order correlations between meteorological variables are low, they represent interactions which influence some coefficients presented in table 7. Partial and multiple correlation coefficients prevent wrong conclusions that might be drawn from this table.

Tables 8 and 9 present partial and multiple correlation coefficients using the following abbreviations:

$$R_y = r(y, \hat{y})$$
$$R_t = r(yT_X, HRS)$$
$$R_h = r(yH, T_X RS)$$
$$R_r = r(yR, T_X HS)$$
$$R_s = r(yS, T_X HR)$$

As an example, R_s is the partial correlation coefficient between the material's property y and the salt deposit S after removal of the correlative influences of the maximum temperature T_X, the absolute humidity H, and the rainfall total R. The symbol R_y denotes the correlation coefficient between the actual material's property y and the corresponding $\hat{y}$ as predicted through linear regression techniques from T_X, H, R, and S.

* Sprouse, Neptune, and Bryan. *Determination of Optimum Tropic Storage and Exposure Sites, Report II: Empirical Data*, TECOM Project No. 9 CO 009 000 006, March 1974.

Table 7. Zero-Order Correlation Coefficients, Means, and Standard Deviations

Predicted Variable	Correlation Coefficients with Meteorological Predictors				Mean	Standard Deviation	Unit	Number of Cases
	T	H	R	S				
Butyl, tensile strength	-.21	+.03	+.04	0	4.38	0.58	Kgf	50
PVC, tensile strength	-.07	-.28	-.22	+.06	4.16	0.26	Kgf	50
Nylon, tensile strength	-.59	-.13	-.15	-.28	9.88	3.79	Kgf	50
Cotton, tensile strength	+.36	-.22	-.40	-.12	109.00	21.00	Kgf	50
Cotton, tensile strength*	+.48	-.09	-.13	-.09	105.00	20.00	Kgf	40
Steel, tensile strength	-.08	-.16	-.41	-.41	106.00	33.00	Kgf	58
Steel, tensile strength*	-.07	-.02	-.10	-.42	98.00	32.00	Kgf	47
Steel, tensile strength†	-.09	-.09	-.01	-.63	103.00	25.00	Kgf	44
Steel, weight loss	+.15	0	+.16	+.32	19.00	17.00	%	58
Steel, weight loss*	+.16	-.12	-.08	+.31	22.00	18.00	%	47
Steel, weight loss†	+.26	-.10	-.37	+.62	19.00	11.00	%	44
T_X, mean maximum temperature	––	-.02	-.06	-.10	85.90	2.40	°F	50
H, mean absolute humidity		––	+.45	+.11	29.80	2.10	mb	50
R, rainfall total			––	+.19	22.00	15.30	inch	50
S, mean daily salt deposit				––	44.90	64.00	mg/m^2/ day	50
T_X*	––	-.03	-.18	-.09	86.00	2.50	°F	40
H*			+.32	+.12	30.20	2.00	mb	40
R*			––	+.16	27.70	12.00	inch	40
S*				–––	48.20	71.80	mg/m^2/ day	40

* Mangrove and shed sites excluded
† Mangrove site excluded

For 50 sets of five data points each, these coefficients must be greater than .38 to reach the 1 percent level of statistical significance, and greater than .29 to reach the 5 percent level.

In general, steel, nylon and cotton deterioration as predicted by multiple regression equations was moderately good, with R_S ranging from .4 to .7. The R for PVC was low (.33) and marginally significant at the 5 percent level. Butyl rubber was very low (.19) and non-significant. The latter finding occurred because of the restriction in range of butyl tensile measures caused by low rates of deterioration.

Inspection of table 8 shows that only three out of 20 reproduced correlation coefficients were statistically significant at the 1 percent level. Table 9 juxtaposes, for the cases of statistical significance of 1 percent and better, the means, standard deviations and standard errors of estimate of the predicted $\hat{y}$.

The following paragraphs comment on different rows of table 8. Scatter diagrams reveal patterns that cannot be derived from the table (appendix C).

Table 8. Correlation Coefficients between Material Tensile Strengths and Meteorological Variables (50 Cases)

(For Symbols See Text)

Tensile Strength	Partial				Multiple
	R_t	R_h	R_r	R_s	R_y
y					
Butyl	-.20	+.02	+.01	+.02	.19
PVC	-.11	-.22	-.13	+.13	.33*
Nylon	-.60	-.09	-.13	-.24	.65†
Cotton	+.37	+.06	-.33	-.10	.49†
Steel					
All 58 cases	-.13	+.06	-.42	-.42	.57†
Sheds excluded (47 cases)	-.08	+.10	-.14	-.43	.44†
Mangrove and sheds excluded (44 cases)	-.07	+.03	-.01	-.63	.63†
Weight Loss of Steel					
All 58 cases	+.16	-.12	+.19	+.33	.40†
Sheds excluded (47 cases)	+.14	-.17	0	+.34	.42†
Mangrove and sheds excluded (44 cases)	+.19	-.08	-.42	+.68	.74†

* Significant at .05 confidence level.
† Significant at .01 confidence level.

The deterioration of nylon was better predicted from meteorological variables ($R_y = .65$) than that of most other material. The clustering observed to a moderate degree in the scatter diagram of PVC (figure C-6) was well developed in nylon (figure C-7) in the sense that exposure at open sites produced the greatest decrease of tensile strength, the sheds less, and the forests least. This finding is significant and underscores a generality of the present study—meteorological parameters are moderately predictive of material deterioration *only* when several different exposure modes are included in the same equation. There is little or no covariation between weather measures and tensile measures within a single exposure mode. See figure C-8 for the most dramatic exposition. The clusters have oblong shapes which, if analyzed within the same exposure mode, would yield regression lines quite different from the equation that encompasses all sites. Since the variation of data within a certain exposure mode is small in comparison with the total variation, the regression functions for modes (open, coastal, shed, forest) are of no practical importance and are not presented here.

Table 9. Several Parameters of Cases in Which the Multiple Correlation Coefficient between Material's Property y and that Predicted by Meteorological Data is Significant at Least at the One Percent Level

y Material, Property*	$\bar{y}$ Mean	S_y Standard Deviation	S_e Standard Error of Estimate
Nylon, tensile strength	9.88	3.79	2.88
Cotton, tensile strength	109.00	21.00	18.30
Steel, tensile strength	103.00	24.60	19.10
Steel, weight loss	19.00	11.20	7.50

*Mangrove and sheds excluded.

Table 8 demonstrates in conjunction with table 9 that there were some statistically significant relations between some material's properties and meteorological data, but that the relations are not high enough for accurate predictions. There are indications that better correlation coefficients may be obtained with other sets of data. The available measurements restricted the investigation in several ways. Especially important was the restriction in range of temperature, the small range of absolute humidity (which is due to the lack of a lengthy dry season in the Canal Zone), and the lack of near-zero rainfall totals at open and forested sites.

In the case of nylon the scatter diagram was further explored. Ambient temperature is produced by conduction and radiation. It is therefore reasonable to divide these components or, under the assumption that the conduction term is of the same order of magnitude everywhere, to assess the radiative component. It was assumed that all open sites have one common component, the sheds have another one, and the forests a third. On the other hand, there is no reason to divide humidity, rainfall, or salt fall in a similar way. Taking this into consideration there are three regression equations which differ only in the factor of the temperature. The data of appendix C for tensile strength produce the equations listed at the bottom of figure C-7 (nylon). Note: The R-term is missing in the second equation because R = 0 in the sheds. The least squares criterion used in the computation of these equations comprised all available measurements.

This change of procedure produced a drastic change of the scatter diagram of the measured versus the predicted values (figure C-8). All points belonging to one exposure mode now lie on narrow vertical strips. This shows that radiation—not measured but represented in the maximum temperature—has an overriding influence on the deterioration of nylon. There is still much scatter within each bar which is not explained by the meteorological parameters used, but must be attributed to factors which did not enter the regression equations and which are as yet unknown.

The observed and predicted tensile strengths of nylon are greater in the forests than in most sheds. This can be attributed to a greater amount of stray light impinging on the samples in sheds than on the forest samples.

Deterioration of cotton was relatively well predicted by meteorological variables when the zero rainfalls of the sheds are excluded (R = .48). Inclusion of the sheds makes the coefficient drop to .36. In both cases, however, the R-value is too small for practical predictions.

Figure C-9 presents the scatter diagram of measured versus predicted values with the sheds included. Whether the shed data are included in the prediction or not, the values from open sites remain clustered, and those from the forests spread over the entire measuring range. Three-way regression analysis which had significant effects for nylon, had no effect on cotton, i.e., the factors of the maximum temperature changed insignificantly with change of exposure mode.

It is well known that corrosion of steel is enhanced by the presence of moisture and salt. For that reason the regression analysis was carried out in three different ways for tensile strength as well as for corrosion weight loss.

Table 6 presents the main results. Because tensile strength has a correlation coefficient of -.80 with corrosion weight loss, part b of table 6 is comparable with the respective rows of part c, generally with a change from plus to minus.

Proceeding from the first to the third lines of parts b and c, the emphasis shifts from rainfall to salt fall when sheds and mangrove are excluded. For instance, for weight loss r_R changes from +.16 (all sites) to -.37 (sheds and mangrove excluded) while r_S changes from +.32 to +.62.

Inclusion or exclusion of the shed sites as areas of zero rainfall can be disputed, especially in the humid tropics where the sheds do not only prevent wetting by rain but also by dew. (Wetting by fog is extremely rare at Canal Zone test sites; but wetting by splashing rain occurs occasionally.)

The corrosion weight loss of steel has a negative correlation with the rainfall total. The negative sign is due to the small weight loss in forests. Obviously, for all practical purposes, permanent wetness in the forest provides a protection against intense rust growth, possibly by filling the cracks in the first rust layer with water, thus preventing oxygen from reaching the metal. At the open sites with their pronounced wetting and drying cycle, more oxygen can penetrate through the cracks in the rust, either directly from the air or dissolved in freshly deposited water.

Figure C-11 demonstrates that the relatively high correlation with meteorological parameters is produced mainly by one coastal site (Galeta Beach), and again the data points are clustered according to exposure mode.

In agreement with nylon, and contrasting to PVC and cotton, the three-way regression analysis (appendix C) results in different values for the factor of the temperature, i.e., it shows a radiation effect. This effect does not result in the same pattern as for nylon. Because nylon is more sensitive to light than to meteorological parameters it confirms that the light intensity in the sheds is stronger than in the forest. This small amount of light is not sufficient to keep the steel dry in the forest where it corrodes more than in sheds. Consequently, figure C-11 shows a better separation of the exposure modes without the overlap of the clusters of dots and triangles as in figure C-10. As in the case of nylon, the vertical dispersion within the exposure modes remains unexplained.

The foregoing analyses indicate that all statistically significant associations between tensile strength and meteorological data reflect differences in exposure mode. Of course, the meteorological conditions are an important factor in shaping the environment, which also shapes the meteorological conditions. For instance, the maximum temperature rises when a site is cleared from dense vegetation. Within one limited area, as in the Canal Zone, it may be assumed that the variations of the modifications of microclimate by man (clearing of forest, reforestation, paving, erection of buildings, etc.) are influential factors reflected in the regression equations. Comparison of Atlantic, mid-Isthmian, and Pacific sites demonstrates that the natural variation of climate across the Canal Zone is of much less influence on the regression equations than the microclimatological modification produced by the mode of exposure. This statement is further borne out by the clustering of meteorological data. Table 10 lists the means and standard variations of the meteorological data used in the 50 cases of regression analyses. Temperature, rainfall, and salt deposit show substantial differences from mode to mode, but temperature and humidity values are restricted in range within single modes.

Table 10. Means and Standard Variations of Meteorological Predictors for Different Exposure Modes (50 Cases)

(Same as Units in Table 1)

	Exposure Modes				
	Coastal	Open Inland	Average	Shed	Forest
Maximum temperature	86.2± 0.97	87.2± 1.33	87.1± 1.32	85.5± 1.67	83.2± 2.93
Mean absolute humidity	30.6± 2.00	30.2± 2.30	30.2± 2.22	28.3± 2.17	30.2± 1.52
Rainfall total	24.3± 16.00	25.6±10.70	25.4±11.50	––	34.0±12.10
Mean salt deposit	162.0±170.4	36.8±24.60	58.4±83.40	31.4±14.00	21.6± 6.10

● **A Case of Weather Sequence Influence on Deterioration of Steel**

It was noted previously that the exposure period which was intended to be representative for the dry season began with an unseasonal period of frequent and copious rains followed by sunny dry-season weather. The change from the wet, cloudy to the dry, sunny weather took place in the third week of January 1972. In two cases the changes in tensile strength were drastic enough to be considered a consequence of this weather change. There are two reasons why not all exposure series showed these results. First, the limited accuracy of measurement resulted in variations that could not be ascribed to the weather change without forcing the data, especially for the materials with only one measurement in 4 weeks. Second, some materials were already so decayed that the change of weather found them in the lower part of the decay curve, and in these curves only drops, not rises, can be expected.

In the 84-day regression analyses discussed earlier, the rainfall data were not analyzed from the standpoint of when the rain fell. This was not done partly because of the limited number of cases, and partly because regression analysis is not adequate for making such a distinction. By using weekly data, however, it can be shown that rain had a definite rust producing effect at open sites and in forests. Figure C-12 shows the decrease of tensile strength of steel during the periods 20 December 1971–14 March 1972, and 7 February 1972–2 May 1972. Days with rainfall are marked by arrows pointing down for the former, and arrows pointing up for the latter. The curves for corrosion weight loss are similar to those in figure C-12 and need not be reproduced.

The total amount of rain as well as the other meteorological variables used in the regression analysis were, within their accuracy, equal in both periods presented in figure C-12. The discrepancy of the curves makes it clear that the total amount of rain was of less importance than the time at which the rain fell. To compare the deterioration rate of the two series, an F-ratio was computed. This analysis assumed linear deterioration rates, for the two series. A significant F-ratio of 184.8 resulted ($\alpha = 0.01$), leading to the conclusion that deterioration was more rapid when frequent rains occurred during the first weeks of exposure. The steel that had been exposed to frequent rains in the first third of the exposure time had 21 percent less tensile strength and 50 percent more weight loss than steel that experienced rain at the end of exposure.

Fortunately, there were also steel samples during both periods in one of the sheds. They showed only small differences in change of tensile strength during exposure time, their trends being opposite to those found in the open and forest exposures. At the sites with rain the tensile strength decreased to 43 percent of its original value when the samples were first exposed to rain, and to 64 percent when rain came at the end of exposure. In the shed the drop of tensile strength was to 94 percent in the first period, and to 86 percent in the period that ended with rain. This is an indication that the differences between the curves depicted in figure C-12 are due to the sequence of rainfall.

Conclusions

● There was no single type of curve that described the tropic deterioration of all materials investigated. However, certain materials were best represented by a single type of curve. A linear decay function was generally more useful than the exponential or double exponential in most cases of tropic material deterioration.

● Successful mathematical modeling requires detailed knowledge of the physical and chemical processes that cause deterioration. These processes are not adequately reflected by tensile tests. The decay function is variable from one material to another, one exposure mode to another, one site to another, and from one time in the exposure cycle to another. Effects were highly variable and required many replications to stabilize them. High variability complicated the prediction problem.

● Tropic meteorological conditions correlated with deterioration only when different exposure modes (forest, coastal, shed and open) are represented in the same multiple regression equations. Within single exposure modes of the same type, meteorological variables did not predict deterioration.

● The multiple regression model does not appear useful for the prediction of tropic material deterioration from climatic measures because of three major problems: (a) restriction in the mathematical range of meteorological values (b) high measurement errors in humidity and radiation, (c) traditional meteorological measures apparently are not the basic causative degrading forces, only contributors and mediators.

● When tropic vulnerability and rapid decay of materials are sought, exposure site selection is more critical than selection of the tropic climatic season. This statement may not be valid for regions with dry seasons better developed than in the Canal Zone. Special care in site selection must be exercised for forest sites because they yield more variable degrading effects than other exposure modes.

- The sequence of meteorological events with respect to exposure time may be more relevant than amount or degree of events. This was found to be true for rainfall in the exposure of steel.

- Steel deterioration is greatest at coastal exposure sites and least at sheltered sites. Protection provided by shelter and/or canopy resulted in lower tensile strength loss. A linear equation was the best predictor of steel tensile strength loss for all exposure modes.

- Cotton deterioration is greatest at forest and coastal sites. Optimal natural environmental conditions for microorganismic growth occur in forests. Solar radiation at coastal sites is responsible for the bond breakage rather than microbiological enzymes which attack cotton at forest sites. The double exponential equation was the best predictor of tensile strength loss at the coastal sites while the exponential equation was best for forest sites. The linear equation was best for open and shelter sites.

- Nylon deterioration is greatest in open and coastal sites. Solar radiation (visible light plus ultraviolet light) plays a major role in bond breakage of nylon. The slower yet extensive deterioration exhibited in sheltered storage is the result of reflected solar radiation as the forest data indicate resistance to microbial attack. The double exponential equation was the best predictor of tensile strength loss at coastal and open sites. The linear equation was best for shelter and forest sites.

- Polyvinyl chloride deterioration is greatest in open and coastal sites. Solar radiation is again the main contributor to deterioration. Also, higher material temperatures result in plasticizer loss. Regression analysis of climatic parameters did not assist in determining deterioration causes. The arrangement within the scatter diagram of measured versus predicted values suggests ultraviolet radiation of shorter wavelengths than measured and/or a specific but unknown factor in the exposure mode. The linear equation was the best predictor for tensile strength loss at the coastal, open, and shelter sites. The exponential equation was best at the forest site.

- Latex deterioration is greatest in open and coastal sites and is very rapid. Solar radiation is the primary cause of deterioration. Ground reflected radiation of longer wavelength may also be the cause of steady deterioration at forest and shelter sites. The double exponential equation was the best predictor for tensile strength loss at coastal, open, and shelter sites. The linear equation was best at forest sites

Recommendations

- The following mathematical equations are recommended for use in predicting tropic deterioration for basic materials during the corresponding exposure modes:

Material	Mode	Equation
Steel	Coastal	Linear
	Open	Linear
	Shelter	Linear
	Forest	Linear
Cotton	Coastal	Double exponential
	Open	Linear
	Shelter	Linear
	Forest	Exponential
Nylon	Coastal	Double exponential
	Open	Linear
	Shelter	Linear
	Forest	Linear
PVC	Coastal	Linear
	Open	Linear
	Shelter	Linear
	Forest	Exponential
Latex	Coastal	Double exponential
	Open	Double exponential
	Shelter	Double exponential
	Forest	Linear

These equations may prove useful to design engineers who must extrapolate from short term tropic tests, or who must estimate tropic material life without benefit of an exposure test.

- Better analytical techniques must be used in future studies of material deterioration. Techniques which allow the selective filtering of some environmental variables, while holding others constant or neutral, hold much promise. Experimental manipulation rather than correlational models are recommended. Results of such work may be used to exclude new materials from tropic use before funds are invested in developmental items that make use of the materials.

- Relevant documents such as AR 70-38* and Test Operations Procedures should more clearly specify the type of tropic exposure modes. For example, Category 2—wet-hot (as described in Section II of AR 70-38) corresponds clearly to open sites in the Canal Zone; whereas, Category 1—wet-warm corresponds to forests with dense canopy only. Forests without dense canopies fit in between the two categories, and should be included as a third category. The most severe exposure modes should be specified when shortened test times are important considerations. In addition, future instrumentation research and development efforts must supplement the traditional meteorological emphasis on temperature, humidity, and rainfall with precise measures of narrow ultraviolet bands, condensation-evaporation cycles, and biochemical contaminants.

- Recommend that no new TOP be developed as a result of this investigation. Instead, recommend that the salient results be incorporated in next revision of USATTC Report 7202001, "Tropic Environmental Effects."†

* AR 70-38, *Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions*, 5 May 1969.
† USATTC Report 7202001, *Tropical Environmental Effects*, Third Edition, February 1974.

SECTION 3. APPENDICES

APPENDIX A. CORRESPONDENCE

(COPY)

DEPARTMENT OF THE ARMY
HEADQUARTERS, U. S. ARMY TEST AND EVALUATION COMMAND
Aberdeen Proving Ground, Maryland 21005

AMSTE-SA 8 January 1969

SUBJECT: Storage of Test Items

Commanding Officer
U. S. Army Tropic Test Center
Drawer 942
Fort Clayton, Canal Zone

1. One of the effects sought in tests of many items of materiel is that of storage. The determination of the storage effects is sometimes accomplished by periodic removal, examination, and operation. An example of the type of materiel which will underg,) this sequence is the Test Set, Chemical Agent Alarm, XM74.

2. One of the many advantages of testing materiel in the Canal Zone is the availability of a variety of tropic environments. Because of this variety and the possibility of different effects of the environments on materials, the question arises as to whether the location of the storage area provides the maximum adverse environment to all types of materials. Conversely, should there be more than one storage area to obtain a better representation of the tropic environments? This question can be illustrated by the several locations used for the test panels.

3. Concurrent with the desire to optimize the storage location(s) is the importance of having a knowledge of the materials used in the assembly of an item and particularly those materials which might be adversely affected by a given environment. Also, there are perhaps other than deterioration characteristics which would result from storage in a specific location and these should be considered together with the types of materials.

4. Your comments on this matter are requested.

FOR THE COMMANDER:

/s/Benjamin S. Goodwin
/t/BENJAMIN S. GOODWIN
Special Assistant

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(COPY)
DEPARTMENT OF THE ARMY
HEADQUARTERS, US ARMY TEST AND EVALUATION COMMANT
Aberdeen Proving Ground, Maryland 21005

Mr. Wise/mgr/234-3350-5221
S: COB 12 October 1970

AMSTE TS-M 18 September 1970

SUBJECT: Determination of Optimum Tropical Storage and Exposure Sites—Phase II, TRMS No. 9 CO 009 000 005

Commanding Officer
US Army Tropic Test Center
ATTN: STETC-MR
Drawer 942, Fort Clayton, Canal Zone

1. Reference USATECOM Regulation 70-12, dated 3 August 1970.

2. This letter and attached TRMS forms 1188 and 1189 (Incl 1) constitute a test directive for the subject investigation under the USATECOM Methodology Improvement Program, RDT&E 1E665702 D625. The estimated cost is $15,000.

3. A methodology investigation proposal (TECR 70-12) based on the summary description of proposal shown in Inclosure 2, must be developed and forwarded to arrive at this headquarters by COB 12 October 1970. The approved methodology investigation proposal will become the basis for conduct of the investigation. Any subsequent deviation from the approved scope, procedure or authorized cost will require approval from headquarters prior to execution.

4. Interim and final reports are due in accordance with the reference. Interim reports will be submitted for each reporting period through the first date following completion of the investigation.

5. New MTP's or required revisions to existing MTP's which are required as a result of this investigation must be prepared and submitted to this headquarters with the final report.

FOR THE COMMANDER:

2 Incl
as

/s/George T. Morris, Jr.
/t/GEORGE T. MORRIS, Jr.
Colonel, GS
Director, Test Systems Analysis

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(COPY)
DEPARTMENT OF THE ARMY
HEADQUARTERS, US ARMY TEST AND EVALUATION COMMAND
Aberdeen Proving Ground, Maryland 21005

AMSTE-PA-M 21 July 1971

SUBJECT: Determination of Optimum Tropical Storage and Exposure Sites–Phase II–TRMS No. 9 CO 009 000 005

Commanding Officer
US Army Tropic Test Center
ATTN: STETC-TS-OP

1. References.

a. USATECOM Regulation 70-12, dated 3 August 1970.

b. USATECOM Regulation 310-6, dated 18 June 1971.

c. Letter, AMSTE-TS-M, USATECOM, 31 December 1970, subject as above.

2. This letter constitutes a test directive for continuing the subject investigation under the USATECOM Methodology Improvement Program, RDT&E 1U665702 D625. The authorized cost is $43,300.

3. Interim and final reports are due in accordance with the references. Interim reports will be submitted for each reporting period through the first report date following completion of the investigation.

4. Special Instructions.

a. The revised methodology investigation proposal (Inclosure 1) is the basis for headquarters technical and financial approval of the subject investigation. Any deviation from the approved scope, procedures or authorized cost will require approval from this headquarters prior to execution.

b. New TOPs, or revisions to existing TOPs required as a result of this investigation, will be developed concurrently and submitted with the final report. The aforementioned TOPs will be developed within the authorized cost. TOP title and number assignments will be requested from this headquarters three months prior to 40 event.

c. Any changes to TRMS that are required will be initiated by TTC.

FOR THE COMMANDER:

1 Incl
as

/s/William L. Stone, LTC
/t/GEORGE T. MORRIS, JR.
Colonel, GS
Dir, Plans and Analysis

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(COPY)

DEPARTMENT OF THE ARMY
HEADQUARTERS, US ARMY TEST AND EVALUATION COMMAND
Aberdeen Proving Ground, Maryland 21005

Mr. Wise/dg/870-5221

AMSTE-PA-M 14 March 1972

SUBJECT: Determination of Optimum Tropical Storage and Exposure Sites (Phase II) TRMS No. 9 CO 009 000 005

Commanding Officer
US Army Tropic Test Center
ATTN: STETC-PD-M
Drawer 942
Ft Clayton, CZ

1. References:

   a. Letter AMSTE-PA-M 21 July 1971, subject as above.

   b. Letter AMSTE-PA-M 10 September 1971, subject as above.

2. Additional funds of $14,000 are provided to the Tropic Test Center to support the subject effort in FY 72.

FOR THE COMMANDER:

/s/William L. Stone, LTC
/t/GEORGE T. MORRIS, JR.
Colonel, GS
Director, Plans and Analysis

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DEPARTMENT OF THE ARMY

HEADQUARTERS, US ARMY TEST AND EVALUATION COMMAND

Aberdeen Proving Ground, Maryland 21005

Mr. Champion/dg/870-5332

AMSTE-ME 31 July 1972

SUBJECT: Determination of Optimum Tropical Storage and Exposure Sites—Phase II, TRMS No. 9-CO-009-000-005

Commanding Officer
US Army Tropic Test Center
ATTN: STETC-PD
Fort Clayton, Canal Zone

1. Reference TECOM Regulation 70-12 dated 3 August 1970.

2. This letter constitutes a test directive for continuing the subject investigation under the TECOM Methodology Improvement Program, RDT&E 1U665702D625.

3. Subject investigation is recognized by this headquarters as a multi-year effort. The authorized cost for FY 73 is $17,400.

4. Special Instructions.

a. The methodology investigation proposal (Incl 1) is the basis for headquarters technical and financial approval of the subject investigation. Any deviation from the approved scope, procedures or authorized cost will require approval from this headquarters prior to execution.

b. The study schedule currently shown in TRMS is still valid.

c. Recommendations on new TOPs, or revisions to existing TOPs, will be included as part of the Recommendation Section of the final report. New or revised TOPs will not be required to be submitted with the final report. Final decision on the scope of the TOP effort will be made by this headquarters as part of the report approval process.

5. In case of conflict, guidance provided in this letter will take precedence over that shown in reference 1a.

FOR THE COMMANDER:

1 Incl
as

/s/Sidney Wise
/t/SIDNEY WISE
Acting Director
Methodology Improvement Dir

Updated 17 April 1972

1. TITLE: Determination of Optimum Tropical Storage and Exposure Sites—Phase II 9 CO 009 000 005

2. INSTALLATION: US Army Tropic Test Center
P.O. Drawer 942
Fort Clayton, Canal Zone

3. PRINCIPAL INVESTIGATOR: Dr. Wilfried H. Portig
Analysis Division
STETC-AD-
Autovon 313-2 85-3202

4. STATEMENT OF THE PROBLEM: In the course of the project "Determination of Optimum Tropical Storage and Exposure Sites" Phase I, much data were collected. There are two types of data: (a) data on material deterioration, subdivided into different kinds of materials, and obtained at different test sites; and (b) environmental data consisting of meteorological, microbiological, and air-chemical information, obtained from the same sites. The problem is the devlopment of a predictive model based on statistical relationship between the materials and environmental data as observed at representative Canal Zone sites.

5. DESCRIPTION OF INVESTIGATION: a. The U.S. Army Tropic Test Center (TTC) will develop a mathematical model that will predict the rate of deterioration of materials as a function of environmental parameters in the Canal Zone. These parameters depend on large-scale features such as geography and macroclimate, and on small-scale features such as kind of exposure, e.g. open, shed, and forest sites.

b. TTC will undertake the following investigations:

(1) Deterioration data will be analyzed from samples exposed on the same day but collected at staggered time intervals (Phase I). Literature survey showed that material properties change slowly at first, then rapidly, and then slowly again, always in a decreasing direction. Such a variation can be represented mathematically through an S-shaped curve described in several ways, e.g.

$$t_D = a_1D+a_2D^2+a_3D^3 \qquad (1)$$

or

$$t_D = \frac{b_1}{1+bD} - b_1 \qquad (2)$$

or

$$t_D = c_1(e^{-C_2D^2} - 1) \qquad (3)$$

in which t_D is the exposure time in which a materials property changed from a value D_o to a value D_t; D in the formulae is equal to the deterioration itself: $D = D_o - D_t$. The a's, b's, c's are constants depending on the environment, on the material and on the kind of measurement symbolized by D.

Formulas (1) and (3) can be solved for the constants by means of straight-forward least square procedures whereas (2) requires iteration by trial and error on a computer.

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(2) Initial data from Phase I have shown that none of the three curves represented by equations (1) through (3) describes all types of material changes during exposure. Three different basic deviations were found.

(a) The inclination of all three types of curves is not flexible enough to follow the partly very steep, partly very shallow slopes of the actual curves. This deficiency could formally be relieved by using higher than the second or third power of D. This would, however, make the formulas very complicated, computation more time consuming, and the constants a, b, c less related to environmental parameters.

(b) It was found that very different combinations of a's can produce very similar curves, whereas small variations in the a's can lead to substantial changes of the curve resulting from them.

(c) The basic assumption of all deterioration hypotheses, namely that deterioration begins with exposure to the elements, is not always true. Some of the materials tested in Phase I showed a marked improvement at certain sites in the first weeks, and only after that they began to deteriorate. Formula (1) cannot be adopted to such deterioration curves and formulas (2) and (3) become more complicated.

(3) The experience described in paragraph 5 (2) requires new approaches.

(a) An analytical formula that describes any deterioration parameter rather well has the form

$$D = d_1 \cos d_2(t^{d_3}+d_4) \qquad (4)$$

The disadvantages are obvious: it can be solved only by trial and error, and it does not readily predict when a certain degree of deterioration will be attained. On the other hand, the d's have very real meanings. For instance D_1 indicated the maximum amount of deterioration, and d_4 indicates if and when there is an improvement in the material before it decays. A disadvantage is the fact that the cosine function rises after falling and in this way precludes any extrapolation of a curve of the type (4).

(b) Deterioration curves can be smoothed through different procedures. Smoothed curves from different similar sites can easily be averaged. Such curves will be constructed and will be a handy information of deterioration of different materials at different types of sites. They are not a mathematical prediction but an easy-to-use tool for the selection of the site at which tests should be conducted and at which season they should be initiated.

(c) Deterioration curves can be approximated through linear regression with environmental parameters. A parameter can be a non linear combination of environmental data. Such a system of regression equations would be a true mathematical statistical mode. There are, however, strong indications from Phase I that the best known elements, ambient temperature and rainfall, contribute little or nothing to the model, whereas there seem to be environmental factors which are not yet sufficiently known, whose insertion in the regression equation might substantially reduce the prediction error. A predictor regression model will be developed that allows the future inclusion of other parameters, and subsequent improvement.

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(4) The development of any model, whether heuristic (para (3)(b) or stochastic (para (3)(c), requires proper presentation and arrangement of the data on which it will be based. The data are being coded and transferred on punch cards. As soon as enough data have been put on punched cards, the data will be transferred to magnetic discs and during the process of transferral they will be rearranged in such a way that they can easily be put in modeling programs of any type.

6. REASONS FOR CONDUCTING INVESTIGATION: a. Present Capability.

(1) Microbiological inspections and services were conducted on 63 tests during the past three years. The information gathered, however, has not allowed the development of cause and effect relationships because the number of test items were limited and could not be destroyed in testing. It is therefore oftentimes impossible to determine or predict the rates, patterns, and reasons for failure of the test items.

(2) The effects of tropic environmental storage are presently determined by the detection of gross changes in materiel (rips, cracks, fading, softening, etc.).

(3) Over 80% of tropic storage testing is conducted at two sites representing only two environmental types.

(4) Many of the storage and exposure sites now available for TTC use were selected for practical reasons with little consideration for significant environmental conditions.

b. Limitations of Present Capabilities.

(l) Present methods (except in Phase I of this project) do not permit following the deterioration process as it progresses with time.

(2) Methods of detecting non-visual deterioration changes on materiel end-items must be developed with the aid of prediction models.

(3) Deterioration rates and patterns must be determined for all major vegetation terrain types available to TTC to assure adequate testing under representatively severe conditions.

(4) A greater number of test sites must be used. Several natural environmental types exist in the Canal Zone, however, the deterioration severity of the sites and their suitability for testing certain kinds of materials has not been ascertained.

c. Anticipated Improvements to Result from Investigation

(1) Establish cause and effect relationships between environment and materiel.

(2) Assist in detecting early manifestations of deterioration.

(3) Establish deterioration rates, patterns and storage periods.

(4) Determine optimum uses of each TTC storage and exposure site by calibrating sites with respect to known severity.

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d. Pertinence to TECOM Mission.

TECOM bears major responsibility for the tropic tests of Army materiel items, thus investigations that will define optimum test sites for equipment will benefit TECOM operations more than any other organization. The present investigation will use non-test data to benefit test methodology.

AMC sponsored deterioration projects (Frankford Arsenal, USAECOM, USAMERDC) in the Canal Zone do not address the same objectives as the present project. The AMC projects are long-term (5—25 years) and are done mostly in coastal sites. The AMC projects are designed to follow the materials through to complete destruction or failure. The present project is designed to yield a higher data rate and to use more sophisticated mathematical analyses than the AMC projects.

7. IMPACT IF NOT FUNDED OR DELAYED: a. Impact statements for the following two conditions:

(1) The investigation will not be conducted.

(a) Effects of failure to fund:

(i) Deterioration predictions at TTC storage and exposure sites cannot be determined.

(ii) Non destructive test methods will not be developed.

(iii) The "Tropic Exposure Considerations" TOP will not be written.

(iv) Scientific and engineering man-hours and $19,521 spent to date would be wasted.

(v) Failure expectancies representative of components used in end item of materiel will not be established.

(b) List of requirements taken from specified requirements documents (QMR, SDR) which will not be met due to inability either to adequately test or analyze the resulting test data.

(i) Small Development Requirement for Remote Area Lightweight Multi-Weapons Armorer's Repair Kit. Be resistant to fungi, insects, mildew, corrosion, moisture and vapor.

(ii) "Be capable of safe storage (5 years) and transportation by individuals participating in missions within an Unconventional Warfare Operational Area under hot-dry, warm-wet, intermediate, and cold climate conditions, as defined in paragraph 8, C1, AR 705-15."

(iii) Small Development Requirement for Army Aircraft Weapons Handling Vehicle, Multipurpose. "Materials will be such as to provide maximum resistance to rust, corrosion and deterioration in service and prolonged storage." "Construction materials used will provide maximum resistance to harmful effects on rodents, fungi, humidity, rain, snow, salt, water, and wind and will have a useful life span of at least 10 years."

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(iv) Small Development Requirement for a Lightweight Camouflage Screening System. "Be resistant to mold, rot, fungus, corrosion, and color fading."

(v) Small Development Requirement for Cold Water Detergent. "Detergent shall remain stable in storage under conditions defined in AR 705-15, para 7a, b, c and d."

(vi) Small Development Requirement for Epidemiological Survey Kit. "The end times contained within the inserts must be resistant to moisture and fungus type deteriorations encountered in hot-wet environment. Exterior carrying case and internal inserts must withstand the moisture hazard encountered on fording small rivers and streams, to the same degree as the Portable Medical Laboratory referred to in paragraph 2b(2)(g)."

(vii) Small Development Requirement for Lightweight Recompression Chamber. "Use construction materials that will provide maximum resistance to harmful effects of rodents insects, fungi, humidity, rain, snow, ice, salt water, and wind."

(viii) Small Development Requirement for a Multicircuit firing Device. "Have a 95% probability of functioning as described in 2c(11) above in wet-warm, wet-hot, humid-hot coastal desert, hot dry, intermediate hot-dry, intermediate cold and cold climate categories after field storage for at least 3 months prior to use and transportation in using unit vehicles or trailers for 3000 miles---."

(ix) Small Development Requirement for Lightweight. Expendable Pallet, Airmobile. "The expandable pallet shall be resistant to all usual weather conditions encountered in Army supply and storage operations in the field." "Preclude softening beyond use under tropic conditions." "Withstand rain(water) that may be expected under monsoon conditions common to S.E. Asia."

(x) Small Development Requirement for a Portable Sign Making Kit. "Be capable of being employed and functioning properly and/or stored under field conditions in hot dry, warm wet, intermediate and cold climatic conditions as defined in para 7, C1, AR 705-15."

(xi) Small Development Requirement for Remote Area Demolitionist's Equipment Kit. "Be capable of being employed and functioning properly and or under field conditions in wet-warm, wet-dry, humid-hot coastal desert, hot-dry, intermediate hot-dry, intermediate cold and cold climatic categories defined in Chapter 2, AR 70-38."

(xii) Small Development Requirement for a Water Quality Analysis Set. "Set shall be capable of operation, safe storage and transportation without permanent impairment of its capabilities from the effects of climatic categories 1, 2, 3, 4, 5, and 6 as delineated in AR 70-38."

(2) The investigation will be deferred until the FY 74.

(a) Effects of delay in funding.

(i) Delay maximum effective use of the natural environments available.

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(ii) Delay the optimum use of TTCs storage and exposure sites.

(iii) Scientific and engineering man-hours and $19,521 spent to date may be wasted.

(iv) Delay the establishment of a Tropic Exposure Considerations TOP.

(v) Delay the establishment of failure expectancies representative of components used in end item of materiel.

(vi) Delay development of nondestructive tropic tests of materiel.

(b) Same as paragraph 7(1)b.

(3) Man hours and dollars spent to date: 1326 man hours and 19,521 dollars.

8. TEST PROJECTS TO BENEFIT FROM THE INVESTIGATION:

TITLE	TRMS NO.	74	75	76	77
Missile, 152mm Heat MGM51	1MI 014 051 002	SU	SU	SU	SU
Missile, Shillelagh, Spt Storage Test	1MI 014 051 008	ST	ST	ST	ST
Rocket Motor M66 Tropic Storage	2MI 111 066 001				
Propellants, Prediction, Safe Life	2MU 005 000 001	PI			
Surveillance Program for S&A Device M30A1 (Nike Hercules)	3MI 080 030 002	SU	SU	SU	SU
Mask, Aircraft, Protective M24	5EI 820 024 005	SU	SU	SU	SU
Mask, Protective, Tank, M25A1	5EI 820 025 001	SU	SU	SU	
Detector Unit, Chemical Agent, Alarm XM8	5ES 300 008 004	SU	SU	SU	SU
Kit, Sampling & Analysis, CBR, M-19E34	5ES 630 019 003	SU	SU	SU	SU
Kit, Chemical Agent, Detector, M18A2	5ES 680 018 004	SU	SU	SU	SU
Burster, Field, Incendiary M4	5MU 018 004 005	SU	SU	SU	
Launcher, Tactical, CS, 16 Tube	5WE F00 008 001	SU	SU	SU	
TOW 15 yr Surveillance Program	8MI 000 TOW 013	SU	SU	SU	SU

9. RESOURCES: a. Financial

	Dollars in Thousands FY73 In-house	Out-of-house
Personnel Compensation		
Permanent Full-time	5.2	---
Part-time		
Travel	2.0	--
Contractual Support	--	--
Consultant & Other Svcs	--	--
Materials and Supplies	1.0	--
Equipment	--	--
G & A Costs	9.2	--
Subtotals		17.4
FY Total		

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b. Explanation of Cost Categories.

(1) N/S

(2) N/A

(3) Contractual support will be required to assist in data analysis, storage and reduction.

(4) N/A

(5) N/A

(6) N/A

7. G&A Costs are computed at tne rate of $15.50 per direct labor man hours. This note provided by TTC Budget Office, includes overhead cost host-tenant agreement support cost.

c. Obligation Plan.

	FY 73				
FQ	1	2	3	4	TOTAL
	17.4				17.4

d. In-House Personnel.

Man-hours, FY 72	Total Number	Required	Available	Man-hours Required
Research Met., GS-1340	1	250	250	250
Microbiologist, GS-0403	1	100	100	100
Materials, Engineer, GS-0806	1	100	100	100
Chemist, GS-1320	1	100	100	100
OR Analyst, GS-1515	1	50	0	50
		600	550	600

Resolution of non-available personnel. OR Analyst is a TDA approved position. Recruitment action is presently at HQ, TECOM. ETA is 1st Qtr FY 73.

10. INVESTIGATION SCHEDULE:

FY 73

	J	A	S	O	N	D	J	F	M	A	M	J
In-house	–	–	–	–	–	R						
Contract												

Consultants: Not applicable

11. ASSOCIATION WITH IMP: Not applicable.

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12. ASSOCIATION WITH MTP PROGRAM: A new Test Operations Procedure wili be written titled, "Tropic Exposure Considerations."

/s/Hyrum Dallinga
/t/HYRUM DALLINGA
COL, Inf
Commanding

(END COPY)

APPENDIX B. REFERENCES

1. Downs and Lawson. *Determination of Optimum Tropic Storage and Exposure Sites, Report I: Survey of Programs in Tropic Materials Research,* TECOM Project No. 9 CO 009 000 006, April 1973.

2. Sprouse, Neptune, and Bryan. *Determination of Optimum Tropic Storage and Exposure Sites, Report II: Empirical Data,* TECOM Project No. 9 CO 009 000 006, March 1974.

3. Foran, Gibbons, and Wellington. *The Measurement of Atmospheric Sulfur Dioxide and Chlorides,* Journal of Chemistry in Canada, May 1965.

4. AR 70-38, *Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions,* 5 May 1969.

5. USATTC Report 7202001, *Tropical Environmental Effects,* Third Edition, February 1974.

APPENDIX C. DATA

Table C-1. Decrease of Tensile Strength with Exposure Time

Steel Exposure Time in Days

Exposure Sites	7	14	21	28	35	42	49	56	63	70	77	84	Standard Error of Estimate
	Percent of Standard Value												
COASTAL													
Pacific	96	92	88	84	80	76	72	68	64	59	55	51	2.9
Atlantic	93	86	79	72	64	57	50	44	37	32	27	22	3.1
OPEN INLAND													
Gun Hill	99	97	95	93	91	88	85	82	79	76	72	69	2.0
Chiva Chiva	99	97	95	92	90	87	83	80	76	73	69	66	2.5
Gamboa	95	92	88	86	83	81	78	76	74	72	70	69	3.1
Fort Gulick	97	93	89	85	81	78	74	70	66	62	58	54	1.4
Coco Solo	97	95	92	89	87	84	81	79	76	73	71	68	4.9
Fort Sherman	98	95	93	90	87	85	82	79	76	73	70	67	1.7
SHED													
Chiva Chiva	99	98	97	97	96	95	94	94	93	92	91	90	0.9
Fort Gulick	99	98	97	96	95	94	93	91	90	88	87	85	1.9
Coco Solo	100	99	98	97	96	95	94	93	92	91	91	90	2.4
FOREST													
Pacific	99	97	95	94	92	90	88	86	84	82	79	77	1.9
Gamboa	96	93	90	87	85	83	82	81	80	79	78	78	3.6
Coco Solo	98	96	94	91	89	87	84	82	79	77	75	72	1.2
Fort Sherman	95	90	86	82	78	75	72	69	67	64	62	61	4.3
COASTAL													
2 Sites combined	95	89	84	78	72	67	61	56	51	46	41	37	1.6
OPEN INLAND													
6 Sites combined	98	95	92	89	87	84	81	78	76	73	70	67	0.8
SHED													
3 Sites combined	99	98	98	97	96	95	94	93	92	91	90	89	1.3
FOREST													
4 Sites combined	96	93	90	87	84	82	80	77	75	74	72	70	1.4
MANGROVE													
1 Site	73	54	41	32	26	21	17	15	13	11	10	9	4.2

Table C-1 (cont) Cotton Exposure Time in Days

Exposure Sites	15	30	44	59	73	89	100	114	128	143	158	169	Standard Error of Estimate
	Percent of Standard Value												
COASTAL													
Pacific	93	86	79	72	66	60	55	51	46	42	37	35	2.7
Atlantic	101	95	90	85	80	75	70	65	60	55	49	45	4.2
OPEN INLAND													
Gun Hill	100	96	93	90	86	83	80	77	73	70	67	64	2.6
Chiva Chiva	99	96	92	88	85	81	78	75	71	68	64	61	3.0
Gamboa	101	97	94	90	87	83	80	77	73	70	66	64	3.4
Fort Gulick	99	96	93	88	83	77	73	67	61	56	50	46	2.1
Coco Solo	99	96	92	89	86	82	80	77	73	70	67	64	6.6
Fort Sherman	102	97	93	89	85	80	77	73	68	64	60	56	3.0
SHED													
Chiva Chiva	99	98	97	97	96	95	94	94	93	92	92	91	1.6
Fort Gulick	99	98	96	95	94	92	91	90	88	87	86	85	1.7
Coco Solo	99	97	96	93	91	88	86	83	79	76	72	69	1.3
FOREST													
Pacific	101	101	99	96	92	87	83	77	71	64	57	52	6.5
Gamboa	98	92	86	80	74	68	63	57	51	45	39	35	11.0
Coco Solo	103	105	106	106	104	100	97	92	86	79	72	66	3.9
Fort Sherman	95	89	80	71	61	50	43	34	26	20	14	11	10.0
COASTAL													
2 Sites combined	96	90	85	79	74	68	64	59	53	48	43	38	3.0
OPEN INLAND													
6 Sites combined	100	96	93	89	85	81	78	74	70	66	62	59	2.2
SHED													
3 Sites combined	99	98	96	95	94	92	91	89	88	86	85	84	1.9
FOREST													
4 Sites combined	102	96	90	84	79	73	68	63	57	52	46	41	5.0
MANGROVE													
1 Site	104	106	107	107	106	104	101	98	93	88	82	77	3.1

Table C-1 (cont) Nylon Exposure Time in Days

Exposure Sites	34	62	92	118	146	174	203	230	258	286	314	342	Standard Error of Estimate
	Percent of Standard Value												
<u>COASTAL</u>													
Pacific	57	48	41	37	34	31	28	26	24	23	21	20	3.4
<u>GALETA</u>													
Atlantic	[illegible]3	54	48	44	40	37	34	32	30	28	27	26	6.5
<u>OPEN INLAND</u>													
Gun Hill	51	43	38	34	31	29	27	25	24	23	22	20	4.0
Chiva Chiva	63	55	48	[illegible]4	41	38	35	33	31	29	28	26	5.2
Gamboa	61	53	48	44	41	38	36	34	32	31	29	28	2.0
Fort Gulick	62	53	46	42	38	35	33	30	28	27	25	24	3.7
Coco Solo	59	51	46	42	39	37	35	33	31	29	28	27	1.8
Fort Sherman	60	52	47	43	40	37	35	33	32	30	29	27	2.3
<u>COASTAL</u>													
2 Sites combined	59	40	44	40	37	34	31	29	27	26	24	23	3.4
<u>OPEN INLAND</u>													
5 Sites combined	60	52	46	43	39	36	34	32	30	29	27	26	1.9
<u>SHED</u>													
Chiva Chiva	92	85	76	69	62	55	48	43	38	33	29	25	5.9
Fort Gulick	88	82	76	71	65	59	53	48	42	36	30	24	5.6
Coco Solo	102	98	95	91	87	83	79	76	72	68	64	61	4.4
<u>FOREST</u>													
Pacific	100	98	97	95	94	92	91	89	88	86	85	83	6.2
Gamboa	100	98	96	94	90	87	82	78	73	67	62	57	3.4
Coco Solo	99	97	96	95	94	92	91	90	89	88	86	85	5.7
Fort Sherman	102	100	99	98	97	96	95	94	93	92	91	90	4.3
<u>SHED</u>													
3 Sites combined	94	88	82	77	71	66	60	55	50	45	41	37	2.5
<u>FOREST</u>													
4 Sites combined	98	96	95	93	92	90	88	87	85	84	82	80	5.0
<u>MANGROVE</u>													
1 Site	94	90	84	80	75	71	66	62	58	53	49	46	6.7

Table C-1 (cont) Polyvinyl Chloride Exposure Time in Days

Exposure Sites	Percent of Standard Value												Standard Error of Estimate
	29	59	92	118	140	168	202	224	252	287	315	343	
COASTAL													
Pacific	93	88	82	78	75	72	69	67	65	63	62	61	3.7
Atlantic	99	96	93	90	88	86	83	80	78	74	72	69	3.7
OPEN INLAND													
Gun Hill	91	89	86	83	81	78	75	73	70	67	65	62	6.3
Chiva Chiva	94	90	87	84	81	78	74	71	68	64	60	57	2.7
Gamboa	95	92	89	86	84	81	77	75	72	69	66	63	1.8
Fort Gulick	94	91	87	84	82	79	75	72	69	65	62	59	3.4
Coco Solo	96	93	89	87	85	82	79	76	74	70	67	65	4.5
Fort Sherman	97	93	89	86	83	79	75	71	68	63	59	55	5.1
SHED													
Chiva Chiva	98	96	95	94	93	93	93	93	93	94	95	96	2.5
Fort Gulick	98	97	96	96	95	95	94	94	93	92	92	91	3.8
Coco Solo	98	98	97	97	97	97	96	96	96	96	95	95	2.7
FOREST													
Pacific	98	97	95	94	93	93	92	91	91	90	90	90	3.9
Gamboa	98	96	95	94	93	93	94	94	95	97	99	102	3.3
Coco Solo	96	96	96	96	96	96	96	96	96	96	96	96	2.4
Fort Sherman	98	96	95	94	94	93	93	93	94	95	96	97	1.7
COASTAL													
2 Sites combined	95	91	87	84	82	79	76	74	72	69	67	65	2.9
OPEN INLAND													
5 Sites combined	95	92	88	85	82	79	75	74	69	65	62	59	1.8
SHED													
3 Sites combined	98	97	97	96	96	95	95	95	94	93	93	93	2.2
FOREST													
4 Sites combined	98	96	95	94	94	93	93	93	94	94	96	97	2.1
MANGROVE													
1 Site	95	94	94	94	93	93	93	93	92	92	92	92	2.8

Table C-1 (cont) Latex Exposure Time in Days

Exposure Sites	Percent of Standard Value 7	14	21	28	35	42	49	56	63	70	77	84	Standard Error of Estimate
COASTAL													
Pacific	21	15	12	10	9	8	7	6	6	5	5	5	2.9
Atlantic	20	15	12	10	9	8	7	6	6	5	5	5	2.5
OPEN INLAND													
Gun Hill	22	16	13	11	9	8	7	7	6	5	5	5	3.5
Chiva Chiva	19	14	11	10	9	8	7	6	6	5	5	5	2.8
Gamboa	24	17	13	11	10	8	7	7	6	6	5	5	2.7
Fort Gulick	25	18	14	12	10	9	8	7	7	6	6	5	2.6
Coco Solo	19	14	12	10	9	8	7	7	6	6	5	5	2.3
Fort Sherman	18	14	11	10	9	8	7	6	6	5	5	5	2.3
SHED													
Chiva Chiva	75	65	58	52	47	43	40	37	34	32	30	28	3.7
Fort Gulick	69	54	43	36	30	25	21	18	16	14	12	10	4.3
Coco Solo	77	69	64	60	57	54	52	50	48	46	44	43	6.0
FOREST													
Pacific	73	66	62	58	55	52	50	48	47	45	43	42	3.3
Gamboa	82	76	71	67	64	61	59	57	55	53	51	50	4.5
Coco Solo	89	84	79	75	72	69	66	64	61	59	57	55	3.0
Fort Sherman	90	86	83	81	79	77	75	74	73	71	70	69	3.8
COASTAL													
3 Sites combined	20	15	12	10	9	8	7	6	6	5	5	5	2.7
OPEN INLAND													
6 Sites combined	21	15	12	11	9	8	7	7	6	6	5	5	2.7
SHED													
3 Sites combined	73	63	55	50	45	41	38	35	32	30	28	26	3.0
FOREST													
4 Sites combined	84	78	73	70	67	65	62	60	59	57	55	54	2.4
MANGROVE													
1 Site	56	43	35	29	24	21	18	16	14	12	11	10	4.2

Table C-2. Usable Combinations between Tensile Strength and Meteorological Data after 84-Day Exposure

Site	Phase	T_X	H	R	S	Tensile Strength: Steel m	Steel p	Cotton m	Cotton p	Nylon m	Nylon p	PVC m	PVC p	Butyl m	Butyl p	Weight Loss Steel m	Weight Loss Steel p
Pacific Coast	II	85.3	31.6	20.4	57.0	27	66	66	76	38	65	78	90	94	102	30	18
	III	86.7	32.0	15.2	24.5	54	70	80	82	42	59	81	89	96	101	37	18
	IV	87.0	28.2	5.9	39.4	79	75	52	87	48	63	86	92	99	101	14	16
	V	86.7	26.6	7.2	16.7	50	76	—	—	—	—	—	—	—	—	35	17
Atlantic Coast	II	87.0	32.4	47.0	392.1	36	23	63	64	36	25	88	91	103	101	24	43
	III	85.0	28.6	33.0	297.1	45	41	74	68	41	51	96	93	101	102	33	35
	V	86.0	32.0	14.1	597.0	14	25	—	—	—	—	—	—	—	—	60	47
Gun Hill	I	86.3	30.6	19.0	27.6	62	69	85	80	41	63	85	90	108	101	15	18
	II	85.3	31.3	27.5	18.8	60	65	75	75	39	67	92	89	101	101	14	18
	III	86.0	34.8	26.2	32.7	73	64	84	75	48	58	89	87	96	101	18	17
	IV	89.0	31.5	9.7	32.0	81	70	77	89	49	46	93	89	99	100	12	18
Chiva Chiva Open	I	90.0	24.7	17.7	31.9	63	65	86	89	47	41	90	90	107	99	19	22
	II	87.0	30.0	28.2	16.6	66	64	73	79	43	59	80	90	104	101	12	20
	III	87.7	27.6	21.2	27.7	80	67	82	84	43	58	88	91	97	100	15	21
	IV	89.3	24.8	8.2	65.0	68	70	73	93	50	51	90	94	97	100	13	23
	V	90.0	24.9	12.0	22.8	67	71	—	—	—	—	—	—	—	—	20	22
Gamboa Open	I	87.3	26.9	28.0	26.1	65	64	84	81	45	60	87	91	102	100	17	22
	II	84.0	28.1	31.4	14.7	70	66	74	73	45	79	86	91	105	102	10	18
	III	87.3	28.9	27.8	38.9	79	63	85	80	45	57	84	90	96	100	15	21
	IV	88.0	28.5	7.8	24.5	58	74	86	89	52	57	95	91	98	100	17	18
Fort Gulick Open	I	87.3	31.2	30.4	40.9	54	60	80	79	44	51	79	89	111	101	23	22
	II	88.3	30.5	43.2	24.5	58	56	74	72	40	59	95	89	107	101	16	22
	III	86.7	29.9	30.9	26.6	68	62	72	78	46	59	81	90	98	101	21	21
	IV	88.0	28.4	15.9	38.1	49	69	75	85	50	57	92	91	100	100	35	20
Coco Solo Open	I	88.0	29.4	28.1	30.5	63	63	88	80	44	56	89	90	105	101	22	21
	II	87.0	32.7	46.7	19.6	68	52	73	90	42	44	83	87	102	101	12	24
	III	85.3	28.9	36.6	23.1	77	59	83	76	46	60	92	90	93	101	17	22
	IV	87.3	29.0	11.9	27.5	64	71	81	87	51	56	100	91	95	100	26	19
	V	89.3	31.8	13.0	14.4	68	70	—	—	—	—	—	—	—	—	17	18

Site	Phase	T_x	H	R	S	Tensile Strength: Steel m	Steel p	Cotton m	Cotton p	Nylon m	Nylon p	PVC m	PVC p	Butyl m	Butyl p	Weight Loss Steel m	Weight Loss Steel p
Fort Sherman Open	I	88.0	33.5	34.5	58.4	70	55	83	76	48	44	91	87	107	101	23	23
	II	87.0	32.3	41.5	39.9	64	54	70	73	43	52	89	88	104	101	10	23
	III	85.3	31.9	22.0	61.0	78	65	86	76	45	64	87	90	96	102	19	18
	IV	87.3	33.1	19.8	134.1	63	58	77	79	48	46	97	89	96	101	24	24
Chiva Chiva Shed	I	83.0	29.1	––	31.9	90	82	103	80	80	87	90	93	104	102	8	11
	II	84.7	28.1	––	16.6	88	82	93	84	84	79	96	93	108	102	5	13
	III	85.0	25.8	––	27.7	94	81	96	86	64	80	95	94	98	101	7	15
	IV	88.0	24.0	––	65.0	90	76	91	93	94	61	101	95	103	100	5	21
Fort Gulick Shed	I	84.0	28.5	––	40.9	81	80	91	82	78	81	91	93	104	102	9	13
	II	84.7	29.4	––	24.8	88	81	90	83	94	77	89	92	110	101	12	13
	III	87.3	30.9	––	26.6	91	78	94	88	77	59	96	90	101	101	4	15
	IV	87.0	28.5	––	38.1	80	78	88	89	70	63	100	92	97	101	3	16
Coco Solo Shed	II	86.3	31.2	––	19.6	87	79	78	86	104	66	86	90	105	101	15	13
	III	85.3	27.7	––	23.1	98	81	83	86	103	76	98	93	95	101	14	14
	V	88.0	31.8	––	14.4	89	80	––	––	––	––	––	––	––	––	8	14
Pacific Forest (Fort Clayton)	I	79.0	29.1	18.0	20.0	75	77	86	65	88	110	83	93	108	104	8	10
	II	81.7	31.6	28.0	17.6	64	69	53	67	108	89	91	90	109	103	3	13
	III	81.0	29.3	24.0	23.3	81	72	86	68	96	96	95	92	96	103	9	13
Coco Solo Forest	II	86.3	31.7	47.0	20.6	65	54	81	71	100	57	96	88	94	101	5	22
	III	88.0	32.5	37.0	19.7	79	58	102	77	97	48	92	87	95	100	7	22
	V	86.0	31.8	13.0	13.2	85	73	––	––	––	––	––	––	––	––	6	15
Fort Sherman Forest	I	82.0	30.7	40.4	26.5	75	62	48	64	108	85	95	90	107	103	10	17
	II	80.7	31.0	52.9	16.7	63	57	24	57	109	92	92	89	102	104	6	17
	III	81.7	30.6	22.2	17.6	81	72	49	69	97	91	92	91	101	103	10	13
	IV	82.3	28.2	20.3	34.5	38	72	47	71	103	88	98	92	100	103	38	14
	V	82.0	28.6	23.6	14.7	91	72	––	––	––	––	––	––	––	––	4	14
Mangrove Swamp	II	86.3	28.5	47.0	12.7	0	55	86	72	76	62	91	90	106	101	100	23
	III	86.0	27.6	37.0	27.9	29	60	105	75	94	65	91	91	99	101	44	22
	V	86.0	32.0	13.0	30.7	9	72	––	––	––	––	––	––	––	––	65	16

Legend:
T_x = mean daily maximum temperature (°F)
H = mean absolute humidity (mb)
R = total rainfall (inches)
S = mean salt deposit on salt candles ($mg/m^2/day$)
m = measured, in percent of standard value
p = predicted, in percent of standard value, based on regression equations

NOTE: Latex not included in this analysis because tensile strengths were nearly zero for most sites after 84 days. The predicted values are based on all available data. For exclusion of shed and mangrove sites see text.

Table C-3. Coefficients and Error Term by Material for the Regression Equation

$\hat{y} = aT_x + bH + cR + dS + e$

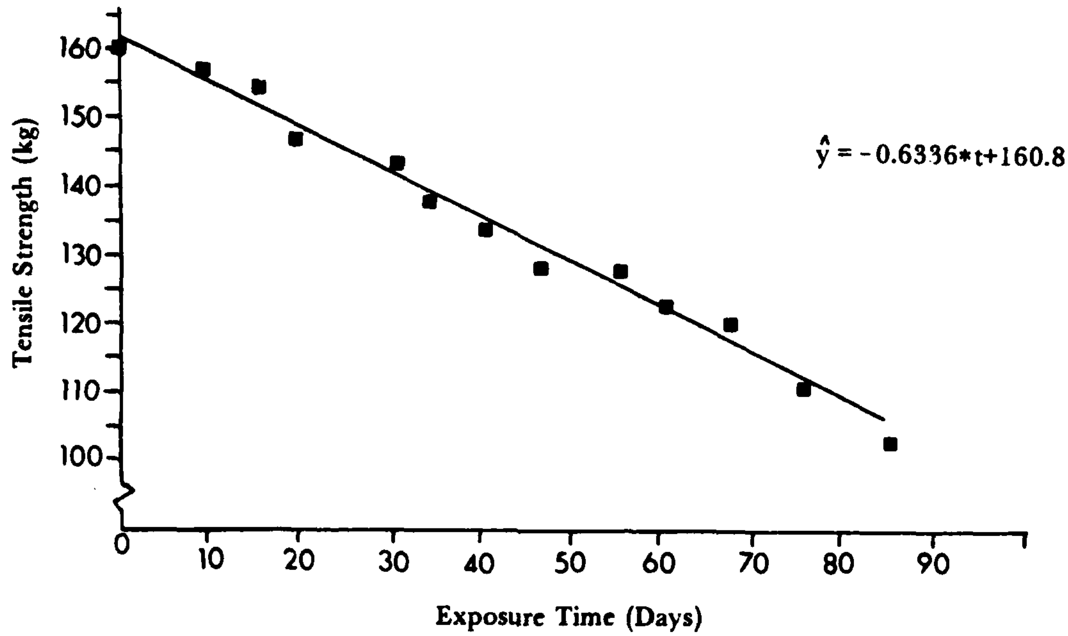
Material	a	b	c	d	e	n	R^2	Remarks
Tensile Strength								
Steel	-0.971	-0.239	-0.533	-0.082	171.8	58	.328	All available cases
Steel	-0.326	-0.778	-0.054	-0.088	119.7	44	.416	Sheds and mangrove excluded
Cotton	+2.215	-0.514	-0.325	-0.020	- 88.6	50	.264	All available cases
Cotton	+2.962	-0.492	+0.002	-0.027	-163.4	40	.253	Sheds excluded
PVC	-0.241	-0.600	-0.053	+0.011	129.8	50	.110	All available cases
Butyl	-0.407	+0.042	+0.004	+0.001	135.2	50	.044	All available cases
Weight Loss								
Steel	1.072	-0.466	+0.195	+0.056	- 66.0	58	.157	All available cases
Steel	0.917	-0.888	+0.031	+0.055	-32.6	47	.178	Sheds excluded
Steel	0.548	+0.370	-0.369	+0.064	-32.2	44	.557	Sheds and mangrove excluded
Steel	-0.786	-0.828	-0.361	-0.091	173.6	55	.473	Only mangrove excluded
Steel	0.770	+0.654	-0.040	+0.064	- 72.1	55	.405	Only mangrove excluded

Legend:

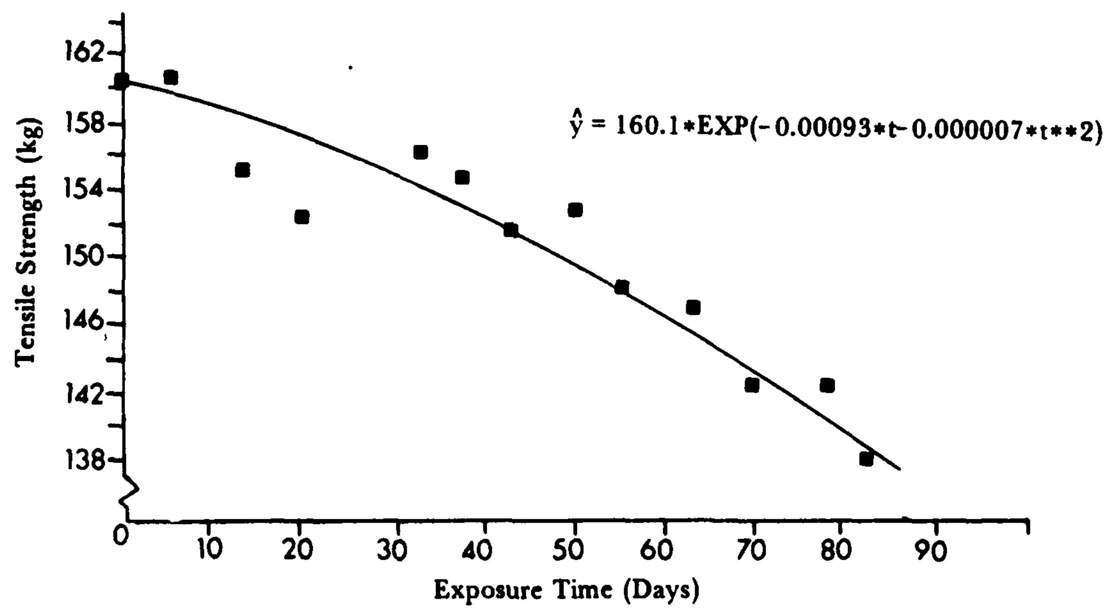
- n = number of cases
- R^2 = coefficient of determination
- T_x = mean daily maximum temperature (°F)
- H = mean absolute humidity (mb)
- R = total rainfall (inches)
- S = mean salt deposit on salt candles (mg/m²/day)

$\left.\begin{array}{l} T_x, H, R, S \end{array}\right\}$ during 84 days

- $\hat{y}$ = predicted tensile strength (weight loss) after 84 days of exposure in percent of standard value
- e = error term

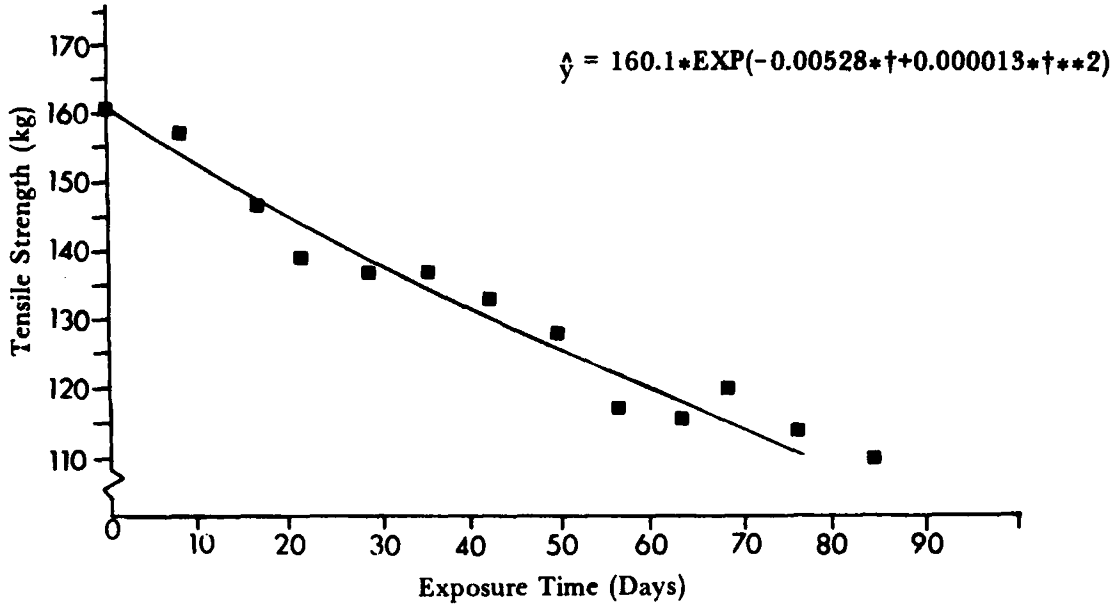


Open Inland

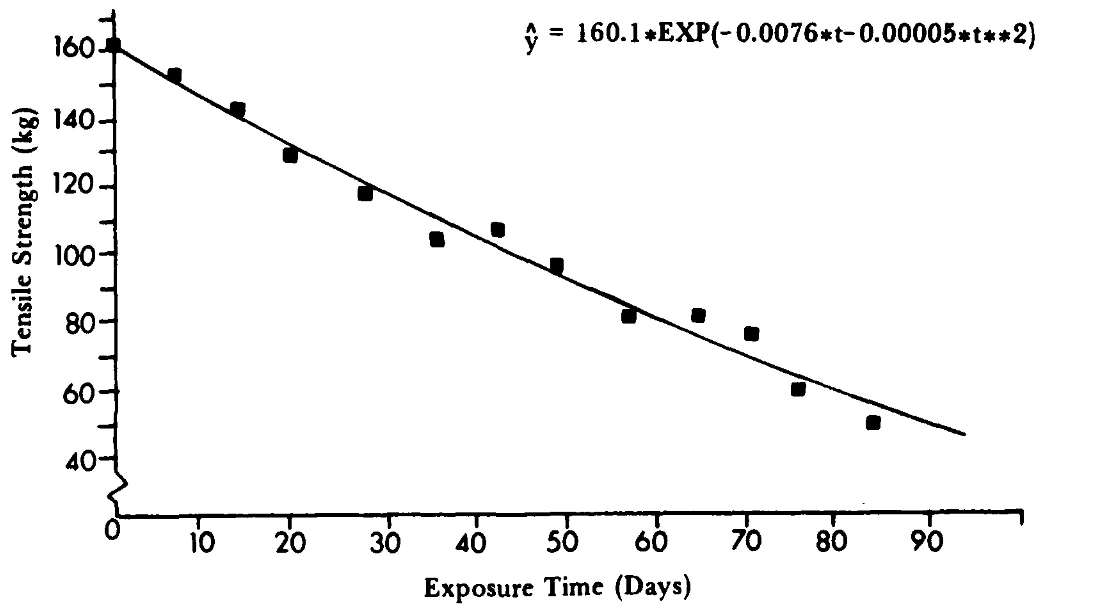


Shed

Figure C-1a and b. Exposure Modes for Steel Material.

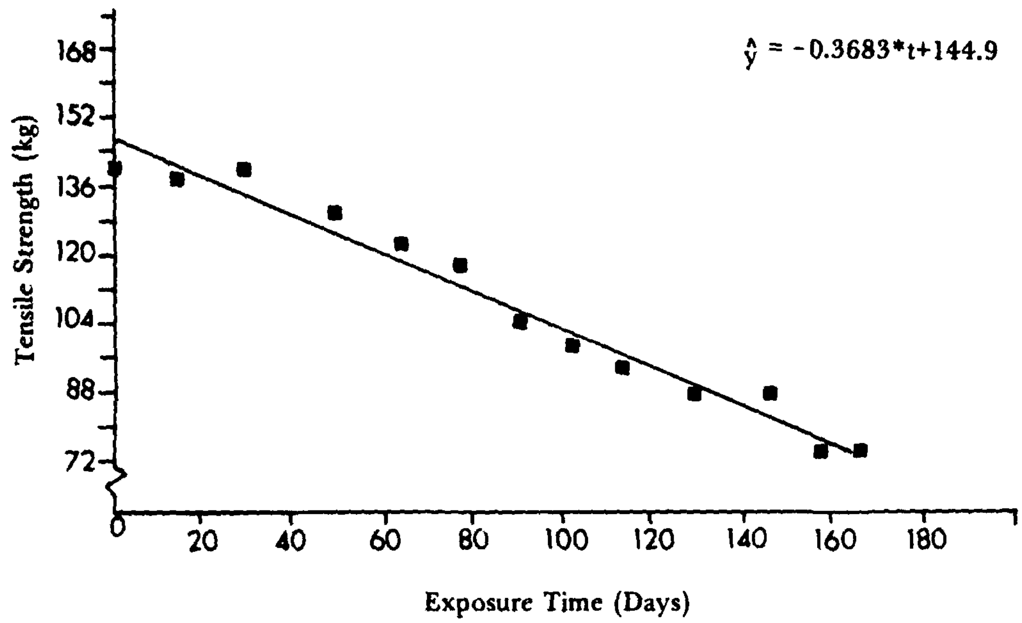


Forest

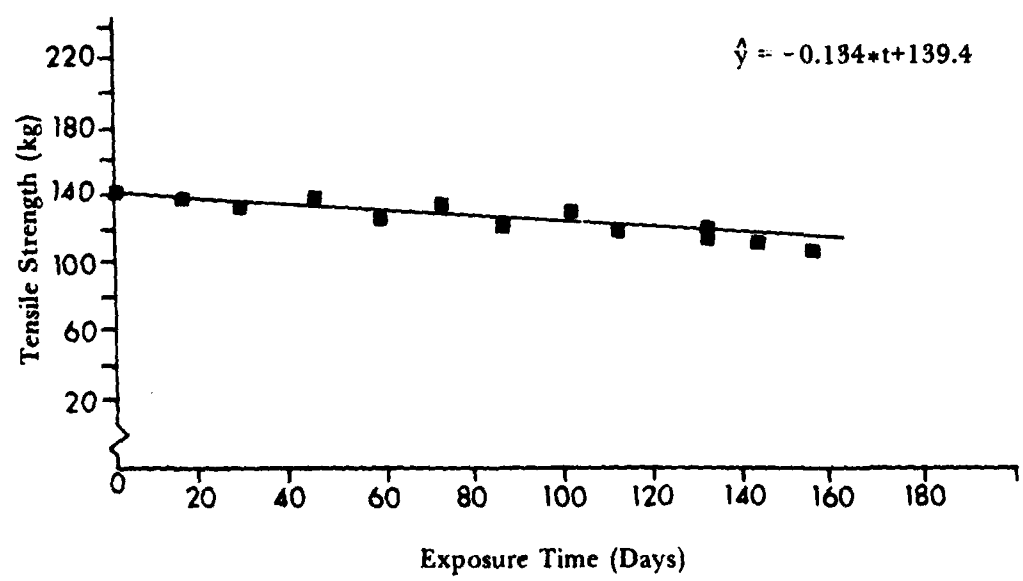


Coastal

Figure C-1c and d. Exposure Modes for Steel Material.

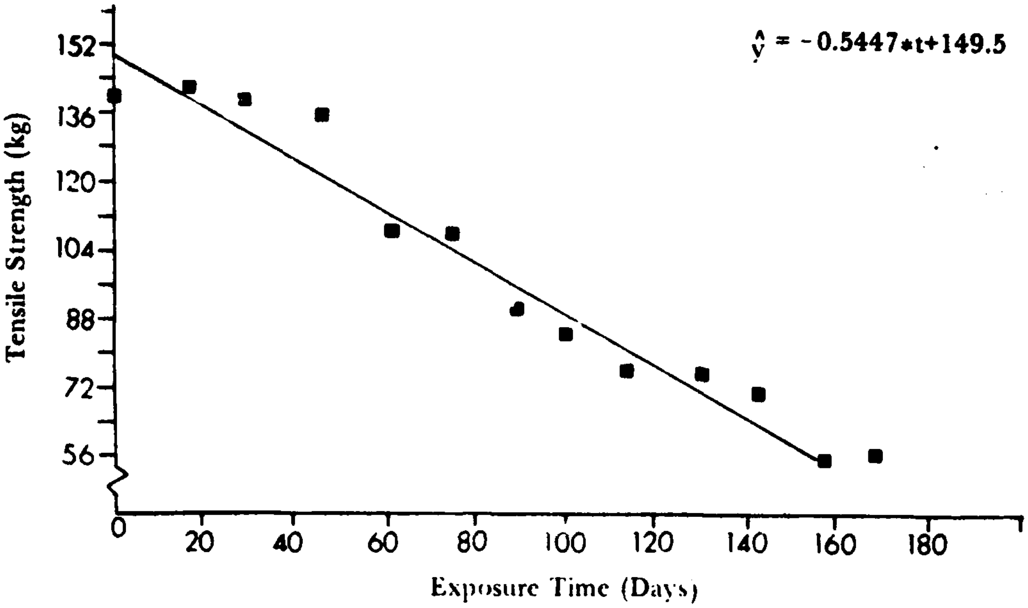


Open Inland

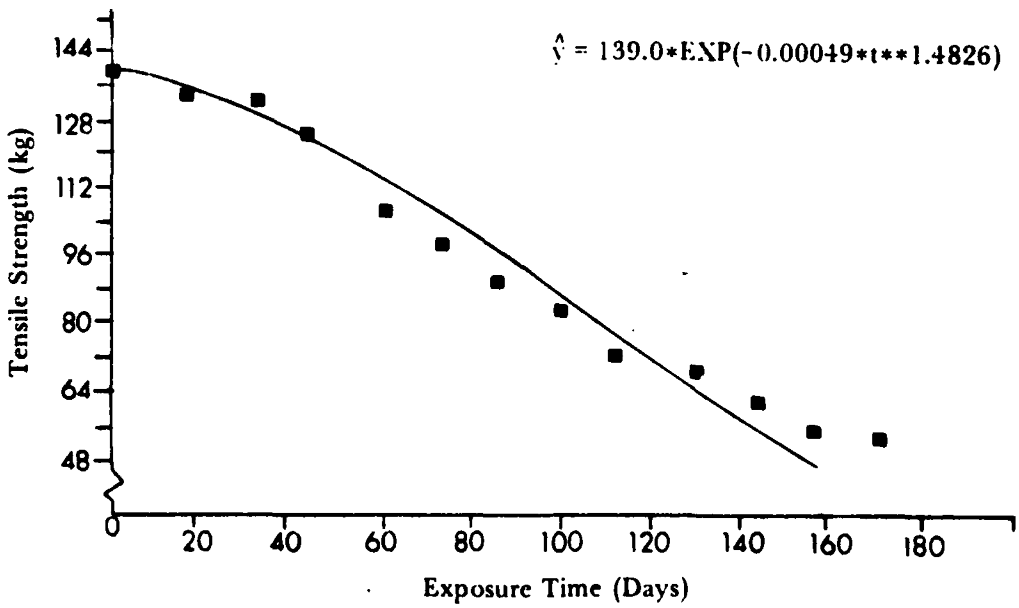


Shed

Figure C-2a and b. Exposure Modes for Cotton Material.

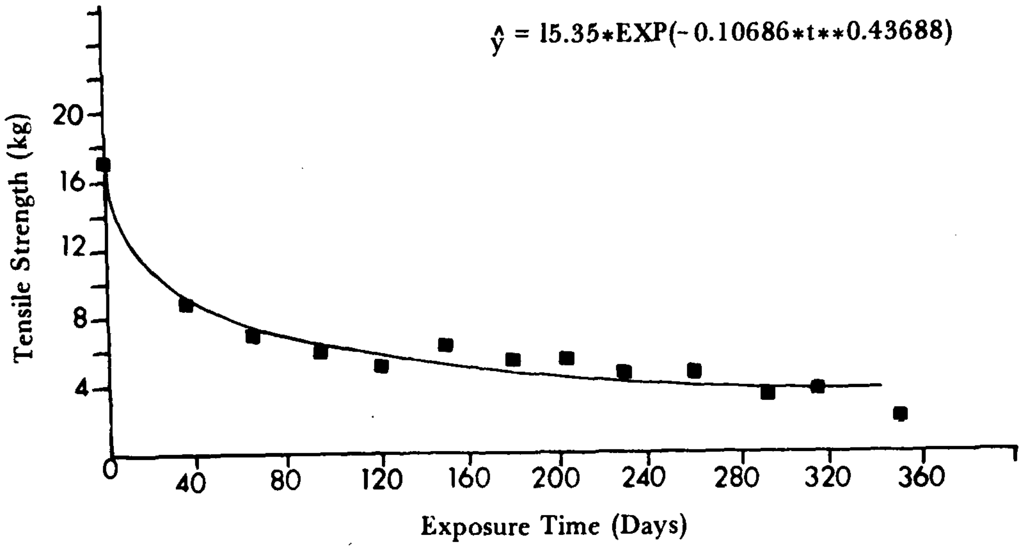


Forest

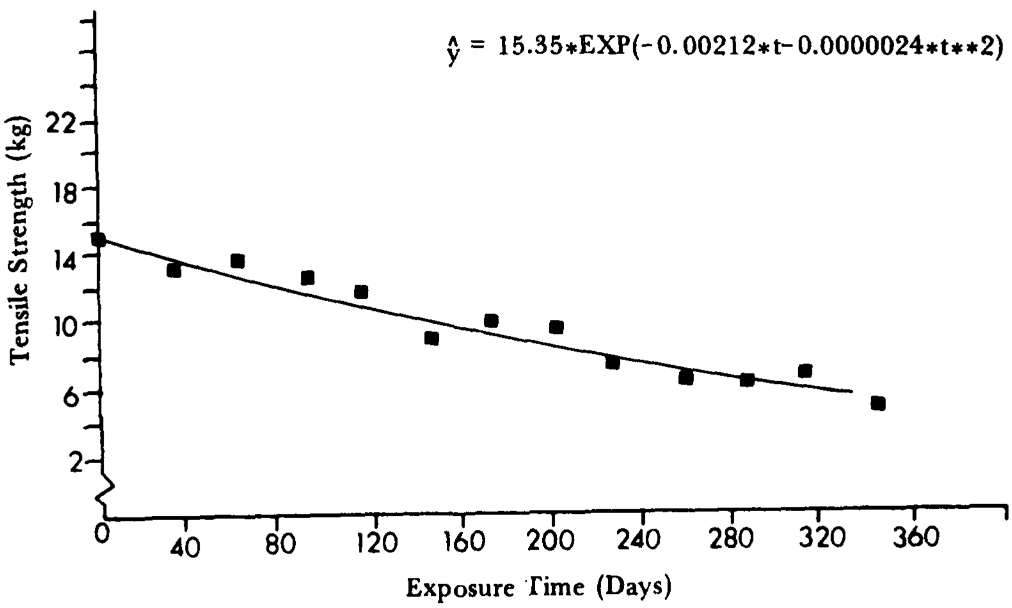


Coastal

Figure C-2c and d. Exposure Modes for Cotton Material.

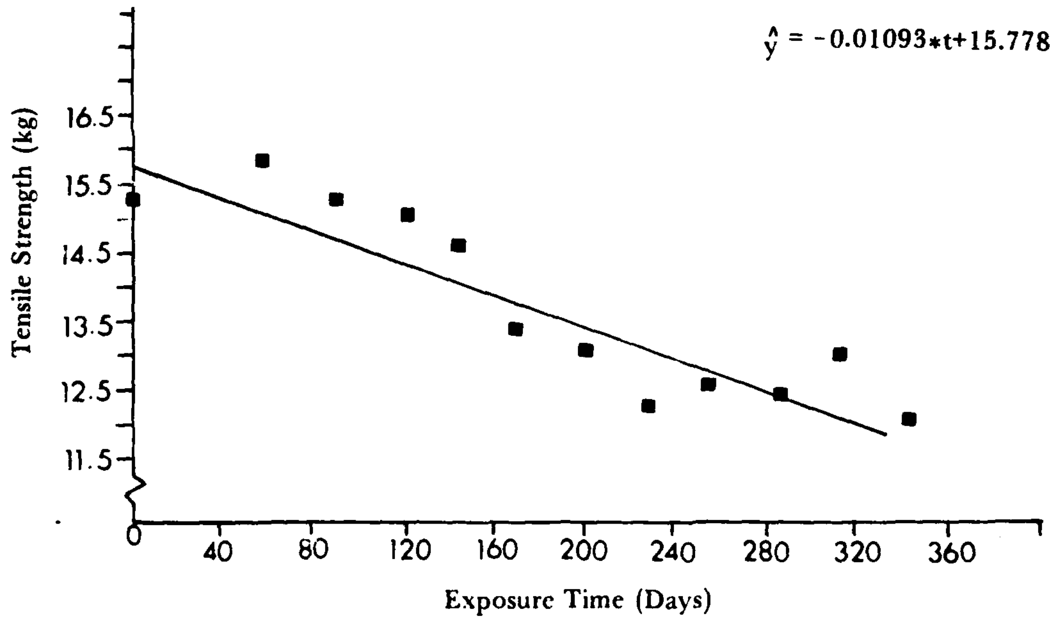


Open Inland

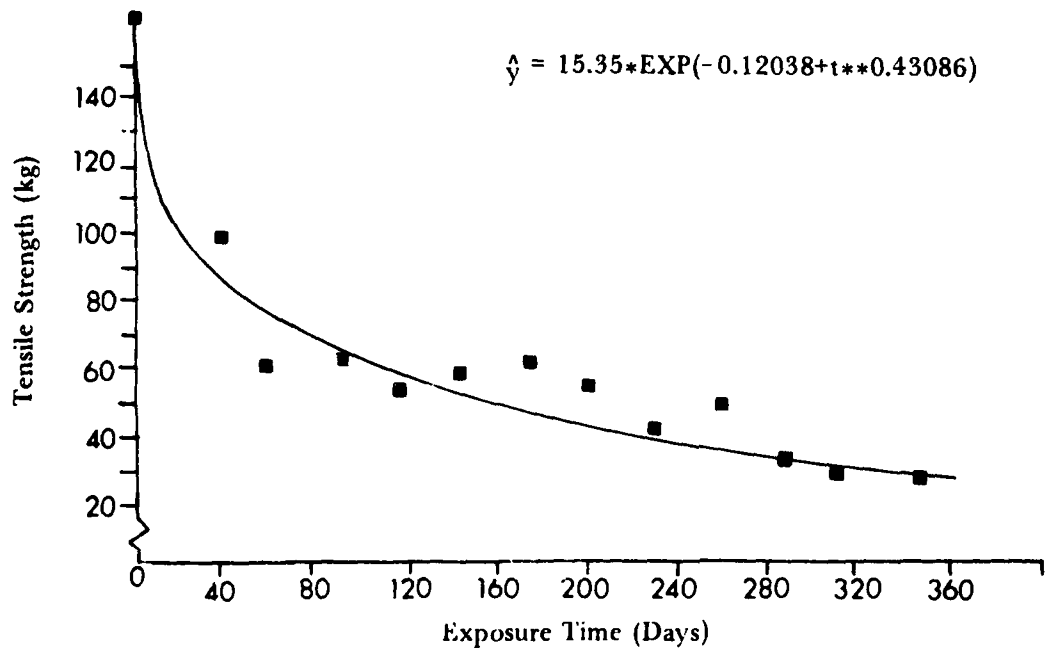


Shed

Figure C-3a and b. Exposure Modes for Nylon Material.

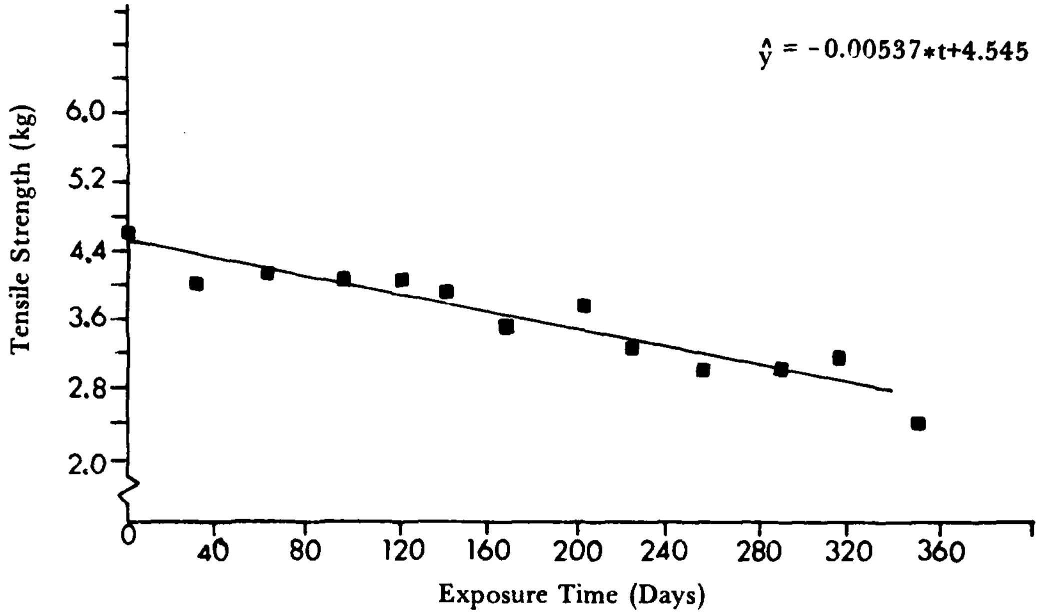


Forest

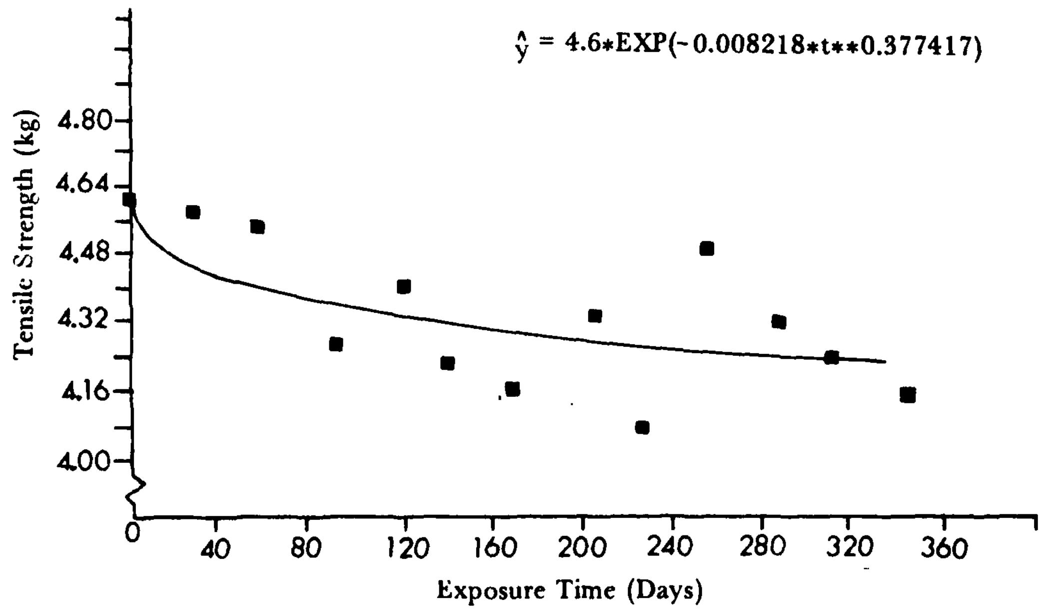


Coastal

Figure C-3c and d. Exposure Modes for Nylon Material.

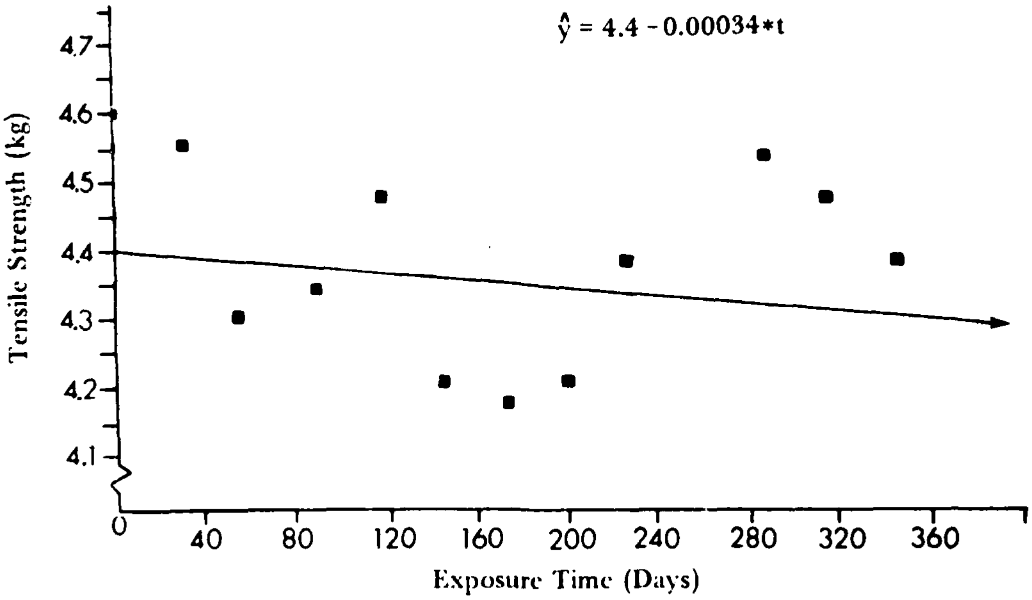


Open Inland

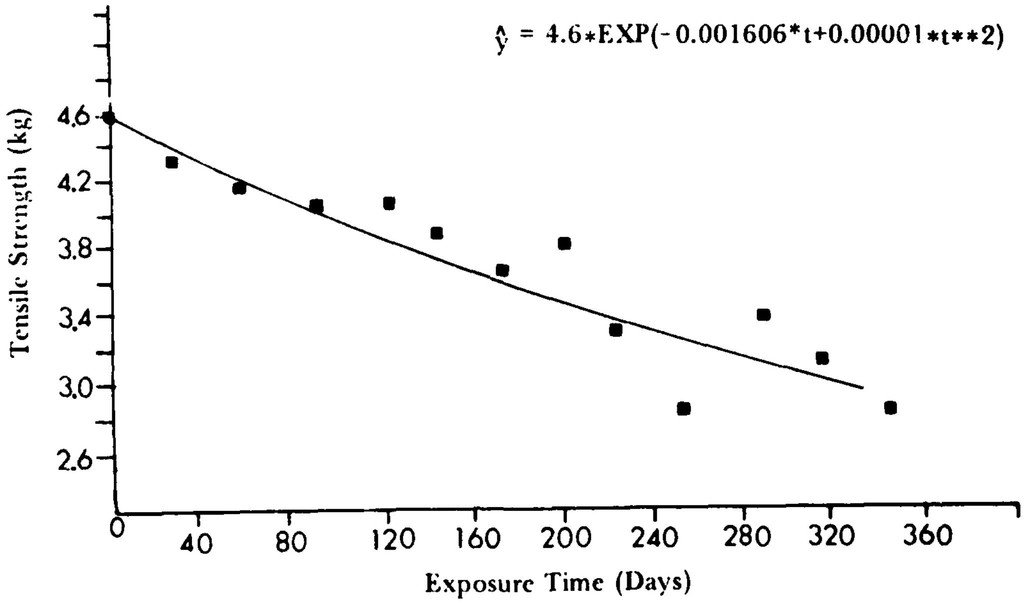


Shed

Figure C-4a and b. Exposure Modes for Polyvinyl Chloride Material.

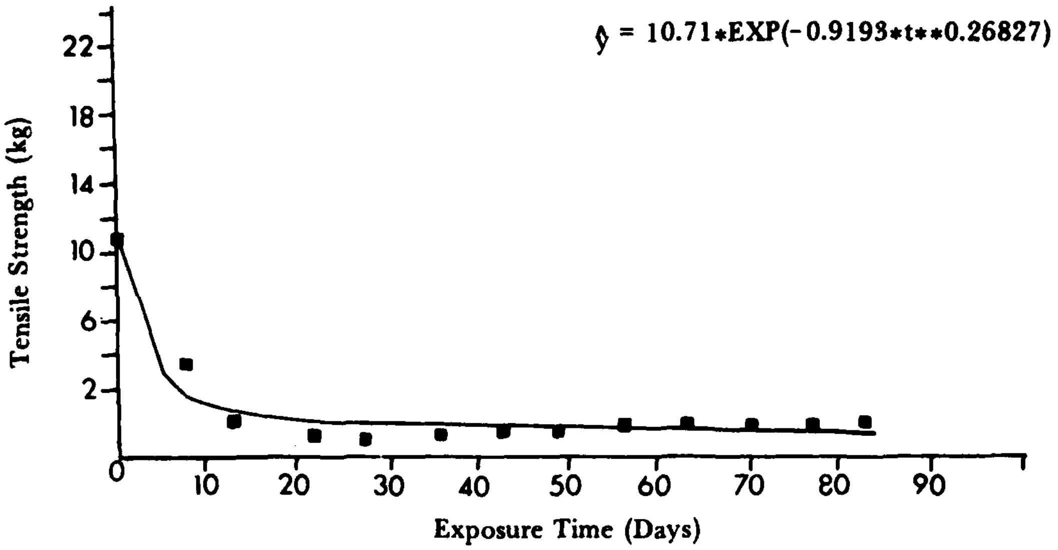


Forest

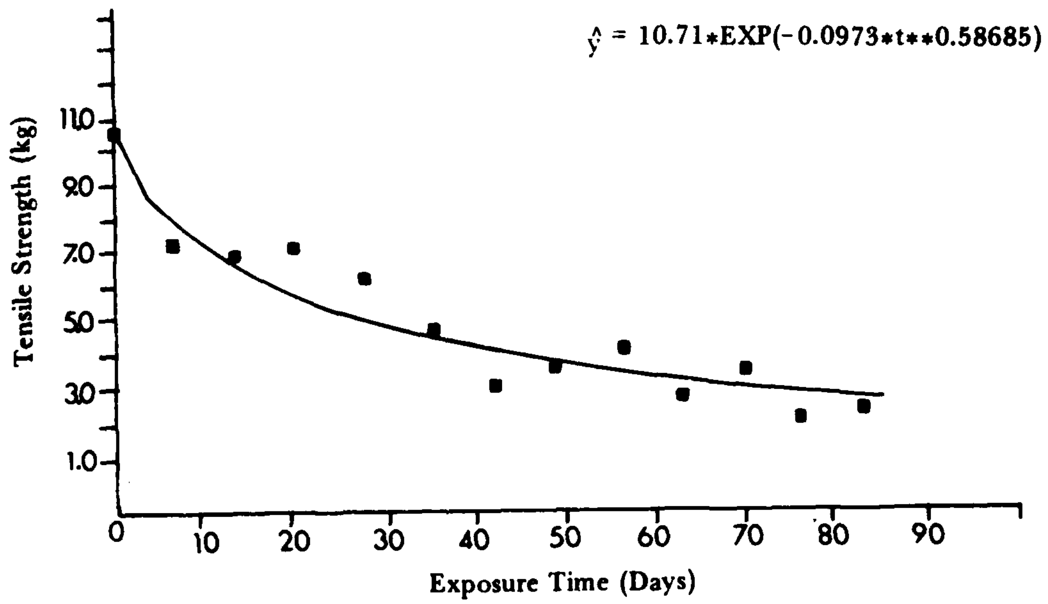


Coastal

Figure C-4c and d. Exposure Modes for Polyvinyl Chloride Material.

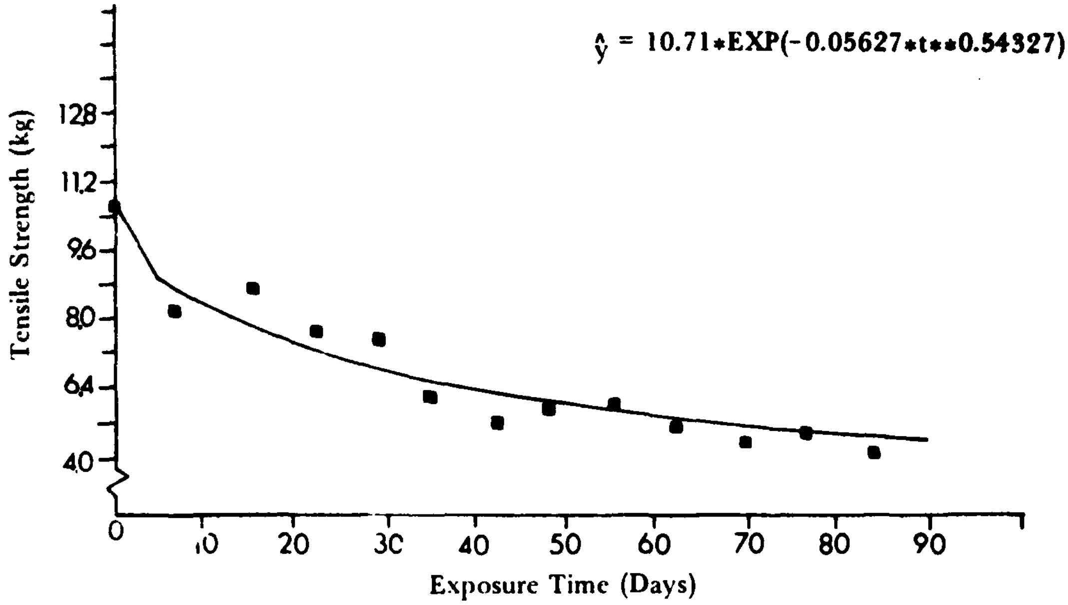


Open Inland

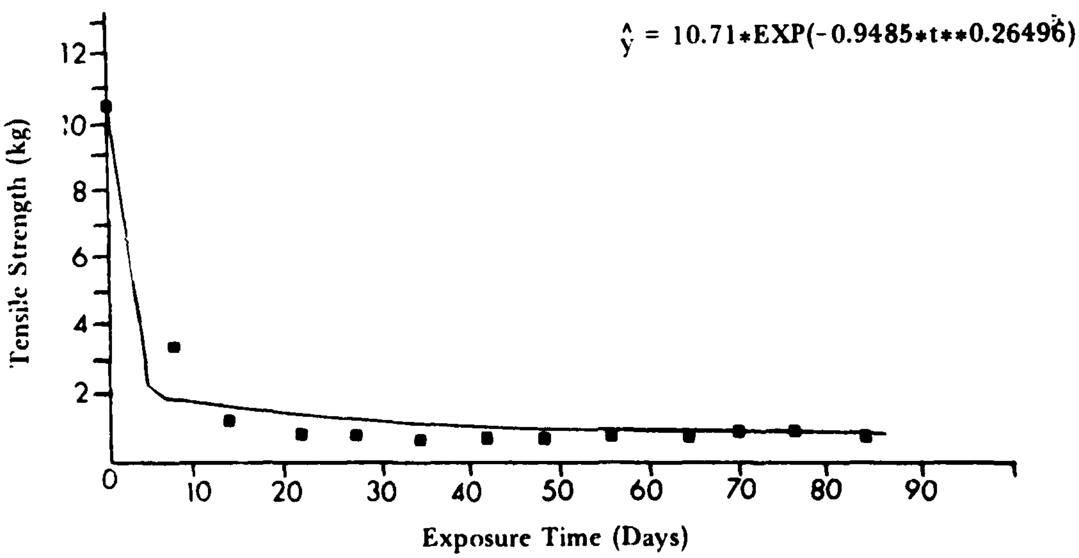


Shed

Figure C-5a and b. Exposure Modes for Latex Material.

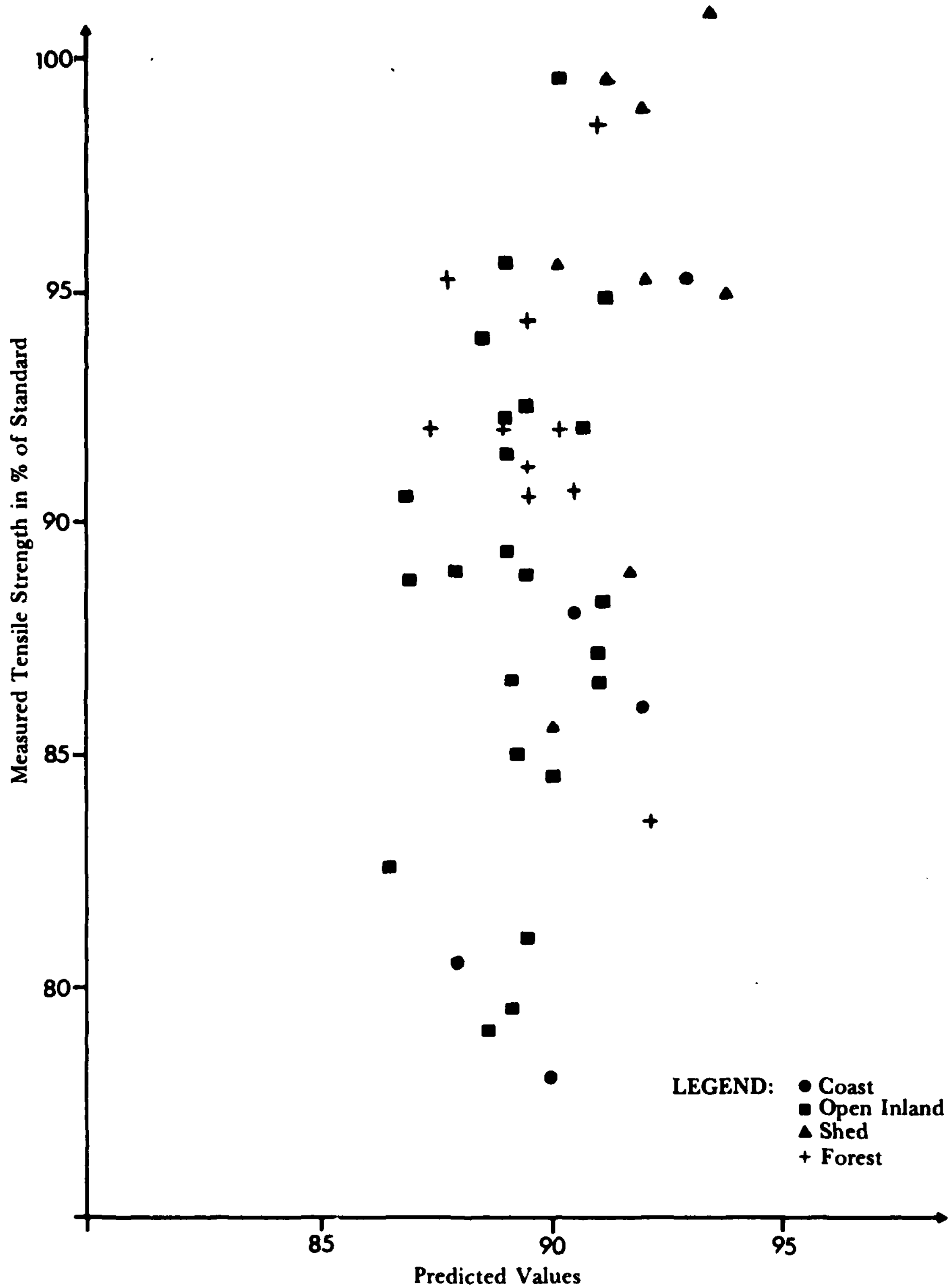


Forest



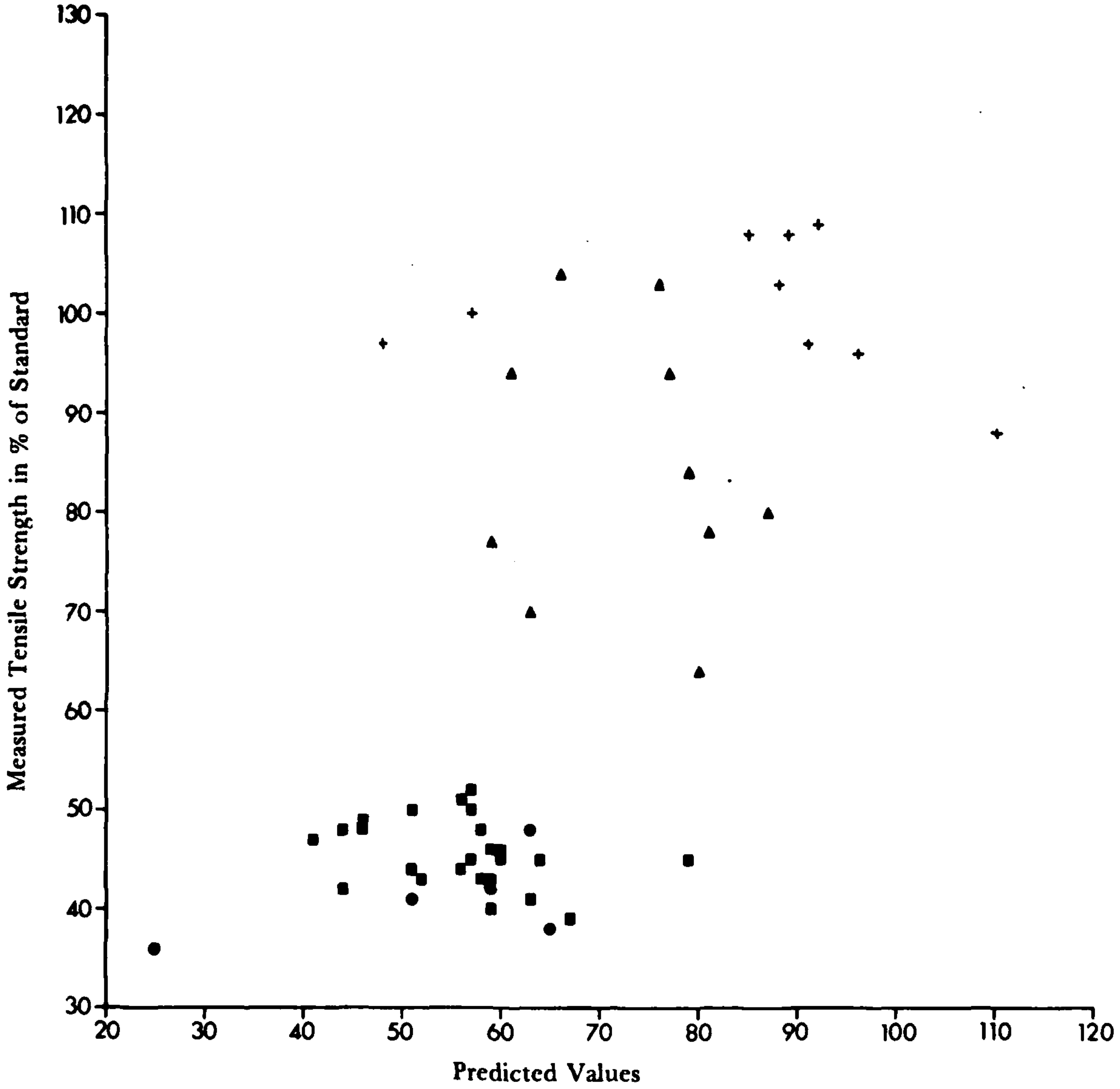
Coastal

Figure C-5c and d. Exposure Modes for Latex Material.



$\hat{y} = -\ 0.241T_x - 0.600H - 0.053R + 0.011S + 129.8\ (R^2 = 0.11)$

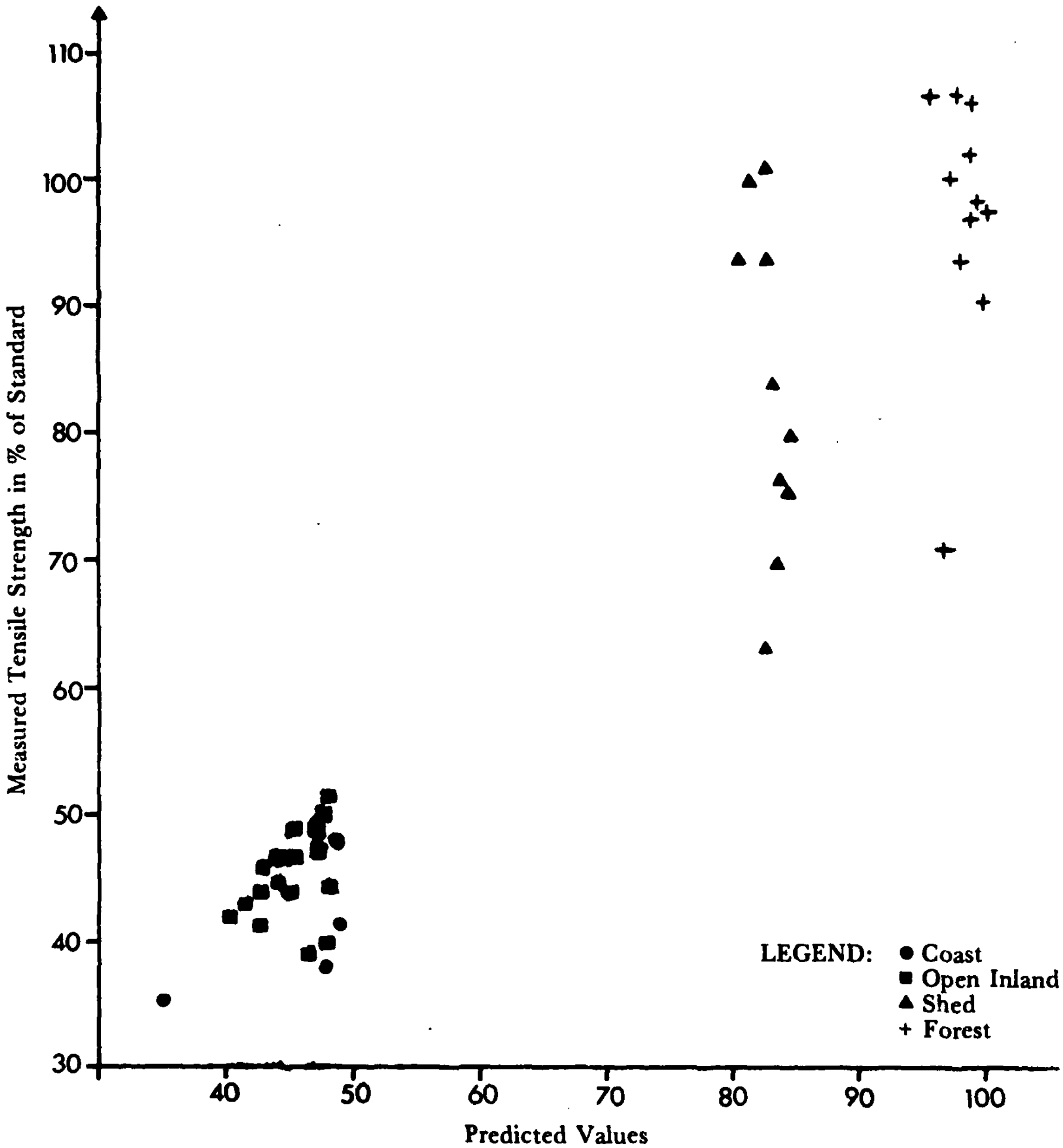
Figure C-6. Scatter Diagram y versus $\hat{y}$ for Tensile Strength of PVC.



$$\hat{y} = -\ 6.076T_X - 1.250H - 0.161R - 0.072S + 630.4 \ (R^2 = 0.429)$$

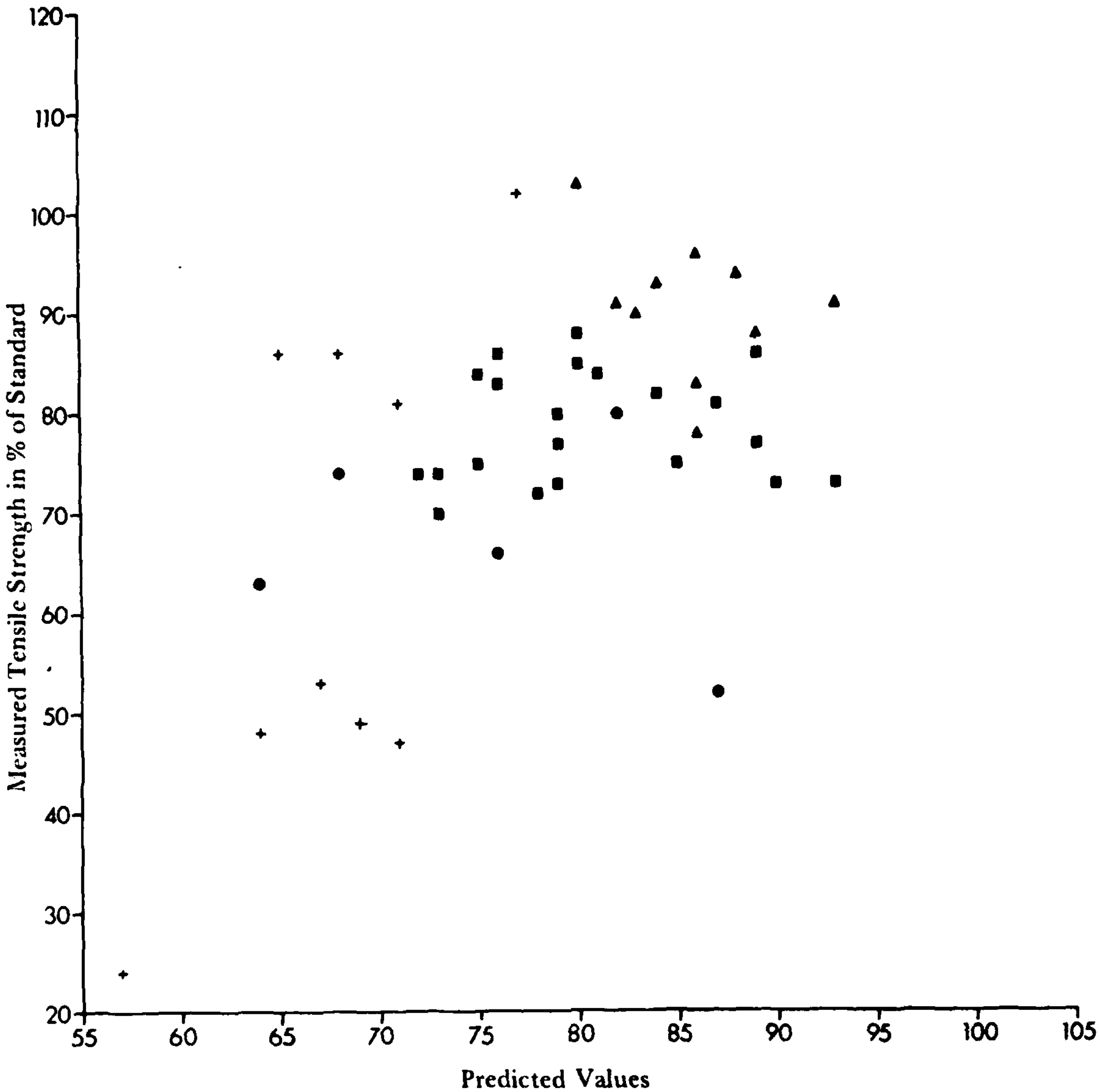
LEGEND:
- ● Coast
- ■ Open Inland
- ▲ Shed
- \+ Forest, Mangrove included

Figure C-7. Scatter Diagram y versus $\hat{y}$ for Tensile Strength of Nylon.



Coast and Open Inland Sites: $\hat{y}_k = -0.534T_x + 0.689H - 0.180R - 0.014S + 75.9$
Shed Sites: $\hat{y}_s = -0.119T_x + 0.689H - 0.014S + 75.9$
Forest Sites (Mangrove included): $\hat{y}_f = +0.087T_x + 0.689H - 0.180R - 0.014S + 75.9$
$(R^2 = 0.898)$

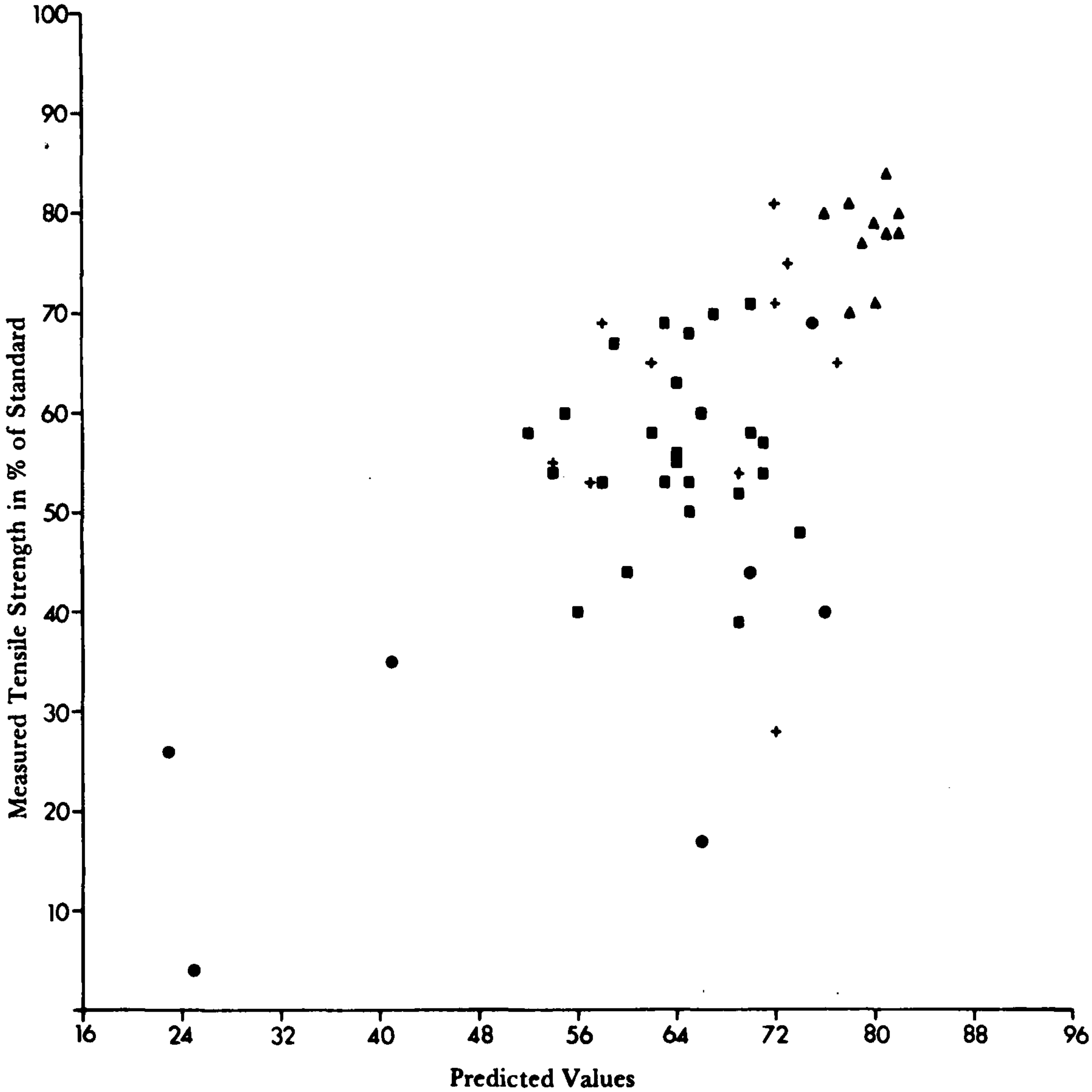
Figure C-8. Scatter Diagram y versus $\hat{y}$ for Tensile Strength of Nylon.



$$\hat{y} = 2.215T_x - 0.514H - 0.325R - 0.020S - 88.6 \ (R^2 = 0.264)$$

LEGEND:
- ● Coast
- ■ Open Inland
- ▲ Shed
- + Forest, Mangrove

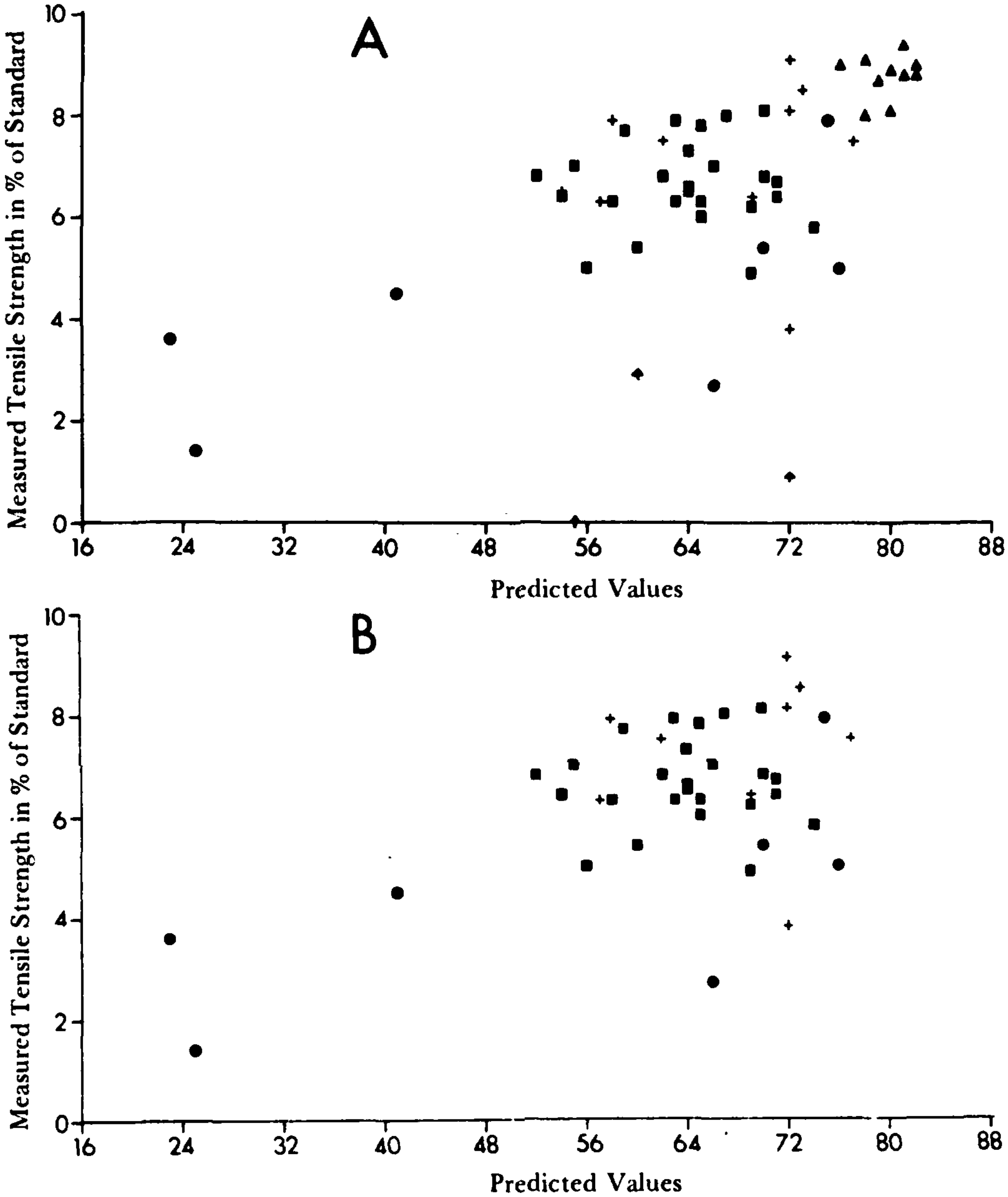
Figure C-9. Scatter Diagram y versus $\hat{y}$ for Tensile Strength of Cotton.



Coast and Open Inland Sites: $\hat{y}_k = -\ 0.253T_x + 0.005H - 0.052R - 0.086S + 90.9$
Shed Sites: $\hat{y}_s = -\ 0.001T_x + 0.005H - 0.052R - 0.086S + 90.9$
Forest Sites (Mangrove excluded): $\hat{y}_f = -\ 0.186T_x + 0.005H - 0.052R - 0.086S + 90.9$
$(R^2 = 0.602)$

LEGEND: ● Coast
■ Open Inland
+ Forest, Mangrove

Figure C-10. Scatter Diagram y versus $\hat{y}$ for Tensile Strength of Steel.



All Available Cases (A):

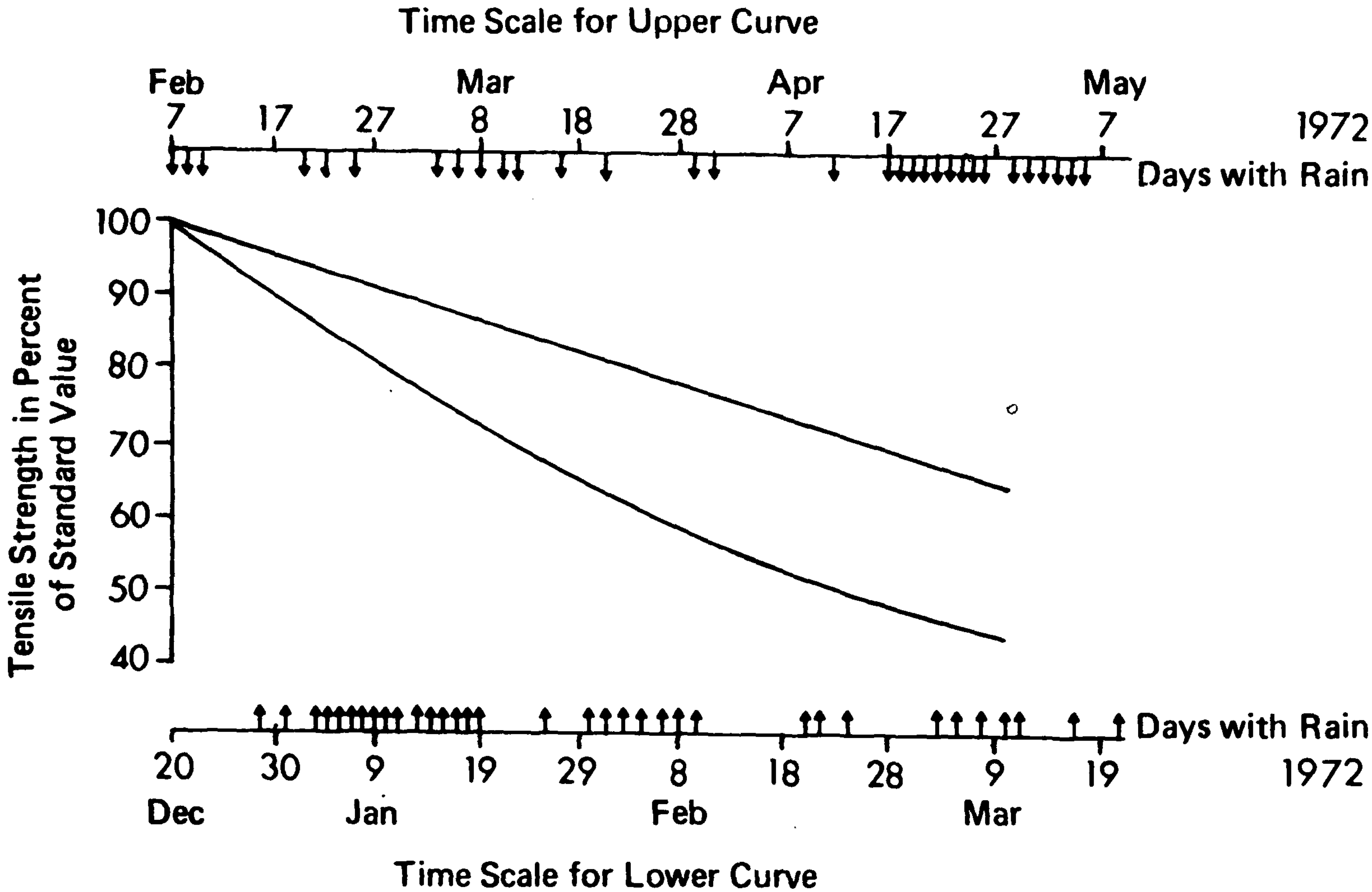
$$\hat{y} = -\ 0.971T_x - 0.239H - 0.533R - 0.082S + 171.8$$
$$(R^2 = 0.328,\ n = 58)$$

Mangrove and Shed Sites Excluded (B):

$$\hat{y} = -\ 0.325T_x - 0.774H + 0.054R - 0.088S + 119.0$$
$$(R^2 = 0.416,\ n = 44)$$

LEGEND: ● Coast
■ Open Inland
▲ Shed
\+ Forest, Mangrove excluded

Figure C-11. Scatter Diagram y versus $\hat{y}$ for Tensile Strength of Steel.



(Average of One Coastal, Two Inland Open, and Two Forest Sites)

Figure C-12. Decrease of Tensile Strength of Steel and Timing of Rain.